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Harnessing the Power of Ocean Energy: A Comprehensive Review of Power Generation Technologies and Future Perspectives

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Abstract: Ocean energy has emerged as a highly promising and environmentally sustainable means of generating renewable electricity, owing to its vast untapped potential. This study focuses on an array of ocean energy technologies, which include tidal energy, wave energy, OTEC (Ocean Thermal Energy Conversion), salinity gradient energy, and ocean current energy. It examines various power generation methods associated with harnessing the power of the ocean. As ocean energy technology is still in the research and development phase, this paper also considers the environmental implications of implementing ocean power plants, such as their impact on marine ecosystems and potential mitigation strategies. The paper presents a compilation of case studies featuring successful ocean energy projects from around the world. It highlights the advantages of promoting this reliable energy source for global power generation, while also addressing the challenges that may arise during the implementation of ocean electricity systems. Furthermore, it explores the future outlook and potential of ocean energy by analyzing emerging technologies, ongoing research developments, and the market's growth prospects. Additionally, it discusses the integration of ocean energy into the overall energy mix, emphasizing its crucial role in achieving a sustainable and diversified energy portfolio. This comprehensive content serves as a valuable resource for comprehending ocean energy and its potential as a renewable energy source.

Index Terms: Ocean energy, Wave energy, Tidal energy, Oscillating water column, Oscillating body converter, Overtopping converter, Power Generation

1. INTRODUCTION

1.1 Background

Urbanization, industrialization, and population growth have played a major role in the substantial increase in global energy consumption. Consequently, there has been a prominent increase in the emission of carbon dioxide into the atmosphere, and it leads to the escalation of global warming. This has resulted in many environmental impacts such as the melting of glaciers, an increase in sea levels, and the occurrence of hurricanes and typhoons that are associated with elevated ocean temperatures.

To reduce the effects of these consequences, consistent with the goals of the Paris Agreement, the international community decided to transition towards an outlook aimed at limiting the increase in global temperatures to a maximum of 1.5 degrees Celsius above pre-industrial levels by the year 2050. To accomplish this, most countries have initiated a transition from non-renewable energy sources to renewable alternatives, intending to achieve net zero carbon emissions. [1]

Among the wide range of renewable energy options available within the global energy transition, ocean energy stands out as a crucial technology that needs to be expanded to achieve complete energy system decarbonization. Ocean Energy has the potential to provide clean, community-oriented, and reliable electricity to coastal countries and island communities across the globe.[2] This review paper aims to provide a comprehensive overview of ocean energy electricity, including its future potential.

1.2 Ocean energy

The ocean is an immense expanse, spanning 140 million square miles (363 million square km), which accounts for roughly 72 percent of the Earth's surface. Approximately 600 million individuals (around 10 percent of the global population), reside in coastal regions at an elevation of fewer than 10 meters above sea level and nearly 2.4 billion people (approximately 40 percent of the world's population) live within 100 kilometers (60 miles) from the coastline. [3] The ocean is abundant in various natural resources that play a significant role in numerous global economic activities. Among these resources, electricity is one of the valuable products that can be derived from the ocean. Due to their potential in mitigating climate change, ocean electricity technologies have attracted significant global attention in the past decade. Fig 01 illustrates the electricity generation trends associated with marine technology over this time frame.

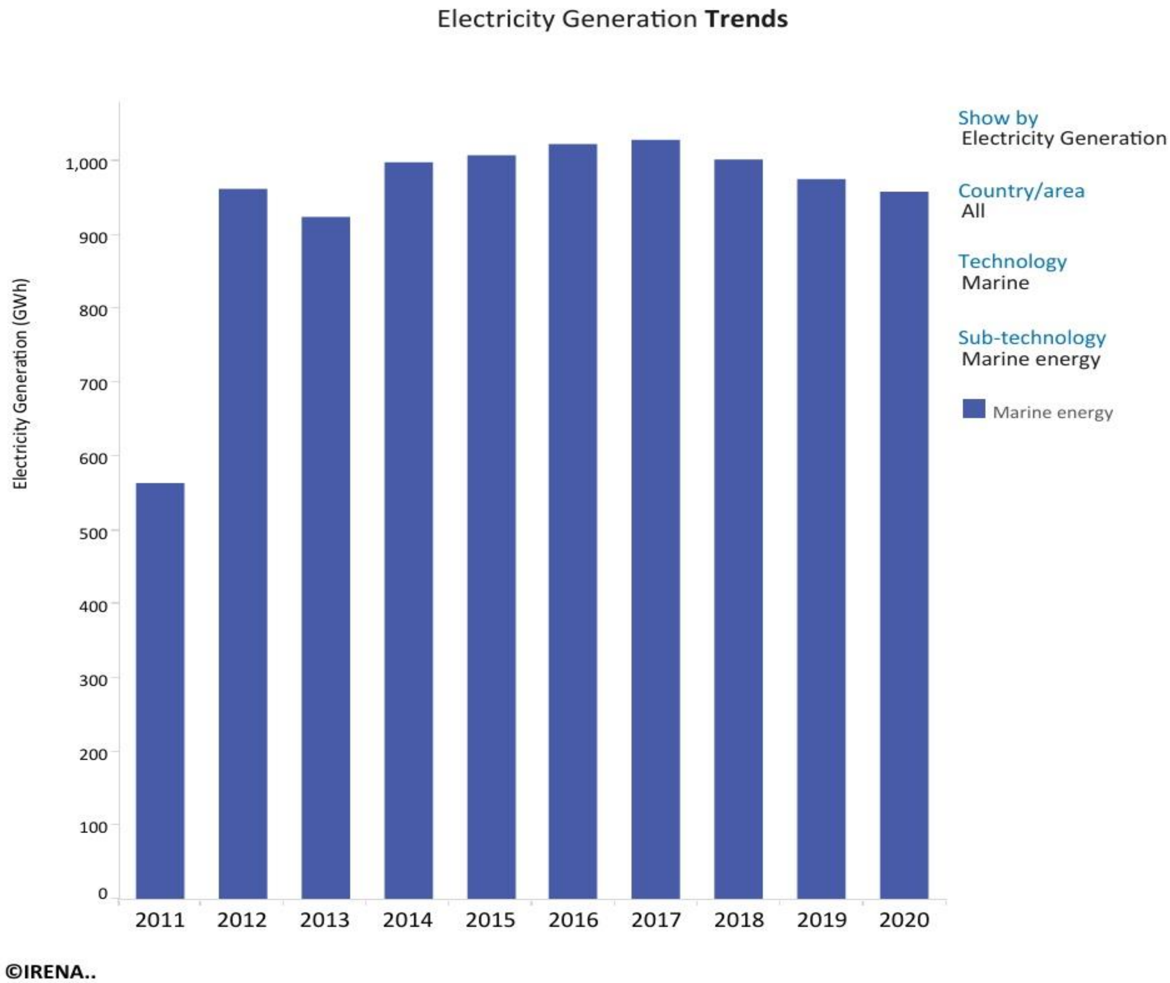


Fig.1. Electricity Generation from Marine Technologies [46].

The theoretical resource potential of ocean energy is immense, and it can meet the current and future global electricity demand. According to the International Renewable Energy Agency (IRENA), the combined value of all ocean energy technologies ranges from 45,000 to potentially over 130,000 terawatt-hours (TWh) of electricity annually. That means ocean energy generation can exceed more than twice the present global electricity demand.

Those ocean electricity energy technologies are typically classified according to the specific resource they harness for energy generation. Tidal stream and wave energy converters have emerged as the most extensively developed technologies across different regions, except tidal range, which is only viable in specific locations. Over time, other ocean energy technologies that derive power from variances in temperature, differences in salinity, or the flow of ocean currents have the potential to gain greater prominence. [4] Hence, the primary focus of this paper revolves around five distinct ocean energy technologies employed for the generation of electricity through various conversion systems. These technologies include tidal energy, wave energy, ocean thermal energy conversion (OTEC), salinity gradient energy, and ocean current energy.

2. OCEAN ELECTRICITY ENERGY TECHNOLOGIES

2.1 Tidal energy

The gravitational forces of the moon and the sun create natural fluctuations in seawater levels known as tides, which can be utilized to generate energy. This energy can be harnessed by capturing the potential energy from the variation in water level or by utilizing the kinetic energy from the flow of incoming (flow) and outgoing (ebb) water when the flow speed reaches at least 1.5 to 2 meters per second.

Based on those two mechanical energy types, tidal energy technologies can be classified into two main categories: tidal barrage (or tidal range) and tidal stream (or tidal current) technologies. Within these two tidal energy technologies, various techniques are utilized globally, encompassing tidal barrage systems, horizontal-axis turbines, vertical-axis turbines, enclosed tips (venturi)/open-center devices, reciprocating devices/oscillating hydrofoils, Archimedes screws/spirals, and tidal kites.

Tidal barrage technology utilizes the tidal range, which refers to the vertical difference between high and low tide, to harness the potential energy. This technology has a relatively long history and has been in operation since the 1960s, making it more mature compared to other ocean energy technologies.

In contrast, tidal stream technologies directly harness the flow of water in open sea areas during both incoming and outgoing tides. These technologies are progressing toward maturity and are anticipated to gain greater prominence in the future compared to tidal barrages. Several technologies are currently being explored to harness tidal currents. While there has been a trend towards the adoption of horizontal-axis turbines in recent years, other innovative technologies are also being pursued that have the potential to significantly enhance the global resource potential for tidal energy. [4]

2.2 Wave Energy

The movement of air across the ocean transfers a portion of its kinetic energy to the surface of the water, generating wave energy. This type of energy encompasses kinetic energy associated with motion and gravitational potential energy.

The waves reach their peak strength within the latitudes ranging from 30 degrees to 60 degrees and are affected by various factors such as wave height, wave speed, wavelength (or frequency), and the density of the water. Due to the spatial distribution, compared to tidal energy, wave energy resources are more widely available.

Wave energy converters are mechanisms designed to capture and utilize the energy present in ocean waves to produce electrical energy. These converters can be conFigured to harness either the kinetic energy, primarily using movable structures, or the potential energy through devices like overtopping systems or attenuators, or even a combination of both.

Throughout time, three primary approaches have been developed to extract energy from waves. The first is the employment of oscillating water columns (OWC), which involve compressing air to power an air turbine. The second method utilizes oscillating bodies (OB) that employ various techniques to convert wave movement in different directions (up/down, forward/backward, side to side) into electrical energy. Lastly, overtopping devices (OD) leverage the potential energy of water overflowing into a confined reservoir, subsequently driving a hydraulic turbine. [4]

2.3 Ocean Thermal Energy Conversion

The sun's radiation is taken in by the ocean and retained as heat in the upper parts. OTEC (Ocean Thermal Energy Conversion) power production utilizes the contrast in temperature between the warm surface and the cool depths of the ocean (around 800 to 1,000 meters below) and transforms it into electricity using a thermal process. In addition to its exceptional capacity, OTEC possesses a significant benefit in that it can deliver uninterrupted, constant baseload power consistently throughout the day.

The initial OTEC test facilities were created during the later part of the 1970s, and currently, OTEC technology remains predominantly in the research and development stage. Unlike wave and tidal technologies, which have commercial entities involved, the key participants in OTEC are primarily research institutes and universities.

Three methods of converting thermal ocean energy are currently being explored: open-cycle, closed-cycle, and hybrid devices. Open-cycle processes involve utilizing warm surface water, which is subjected to low pressure and rapidly evaporated to create steam. This steam acts as the working fluid for generating energy. Closed-cycle systems, on the other hand, do not directly evaporate the warm water. Instead, the warm water is used to evaporate a different working fluid with a lower boiling point than water, through a heat exchanger. This evaporated working fluid is then employed to produce energy. Hybrid systems combine elements of both closed and open cycles. They employ closed-cycle processes and subsequently sequentially use open-cycle methods. [4]

2.4 Salinity Gradient Energy

Salinity gradient energy, also referred to as osmotic energy, harnesses the pressure potential resulting from variations in salt concentration within the ocean. This renewable energy source utilizes membranes to convert the salinity difference into usable power.

The salinity of the ocean is not uniform worldwide; it tends to be lower near the poles due to melting ice. Other factors like river runoff, glacier melting, and precipitation patterns, also contribute to varying salinity levels in specific regions. To maximize energy generation, it is crucial to identify areas with significant differences in salt concentration, such as river beds where freshwater meets saltwater, creating an efficient setup for power generation. Estuaries, which can be found globally, present suitable conditions for continuous operation, enabling them to provide stable baseload power.

Currently, two primary processes are being tested and implemented to tap into this potential energy: pressure retarded osmosis (PRO) and reversed electrodialysis (RED). In a PRO system, a freshwater chamber and a seawater chamber are separated by semi-permeable membranes. The RED system, on the other hand, directly utilizes the salt ions present in seawater and eliminates the need for a turbine. It employs perm-selective membranes to separate the ions and arranges them in RED stacks to amplify the chemical potential difference. [4]

2.5 Ocean Current Energy

Besides the ebb and flow of tides, ocean currents serve as another mechanism of movement in the oceans. These large circulations are initiated by the interplay of wind, temperature, and salinity on a global scale.

Ocean currents typically have slower speeds compared to tidal streams, but they possess significantly higher volumes and magnitudes. One advantage they have over tidal streams is that they flow continuously and uni-directionally with minimal fluctuations, unlike the bidirectional flow of tides. This characteristic makes ocean currents highly suitable for generating steady and constant baseload power.

Although ocean current harnessing technologies have been scarcely tested, they are anticipated to be similar to those used for tidal stream energy. The focus has primarily been on hydrokinetic devices designed to accommodate the lower speed of ocean currents. However, new tidal technologies capable of operating at lower speeds are emerging, making it uncertain which technology will be employed for electricity generation from ocean currents.

The environmental impacts of this technology remain largely unknown and complex to assess. Consequently, the level of development in harnessing ocean current energy is lower compared to other forms of ocean energy. It is expected that once tidal energy becomes fully commercialized and long-term studies become available, more attention will be directed toward extracting energy from ocean currents. [4]

3. POWER GENERATION TECHNOLOGIES

Ocean wave power generation is a promising technology that harnesses the energy present in ocean waves to generate electricity. Waves offer a more predictable and consistent energy source compared to wind or solar power. Wave energy production is smoother and more reliable, resulting in higher capacity factors. With waves originating from storms far out at sea, wave power can be harnessed over long distances without significant energy loss. Wave energy is also more space-efficient than wind power and requires less infrastructure.

The efficiency of wave power generation depends on a number of factors, including the wave height, the wave period, and the design of the wave energy converter. The efficiency of current wave energy converters is typically in the range of 20-30%. However, there is potential for the efficiency of wave power generation to improve in the future.

Tidal energy conversion systems use the rise and fall of tides to generate electricity. There are two main types of tidal energy conversion systems:

3.1 Tidal energy conversion systems

3.1.1 Tidal barrages: These are dams that are built across tidal estuaries. The gates of the barrage are opened when the tide is high, and the water flows through the barrage, turning turbines to generate electricity [5]. Fig.2. shows how tidal barrage power production works by showing how the tidal currents and the barrage structure work together. The picture shows how tidal energy can be used by putting turbines in the water and letting the waves turn them.

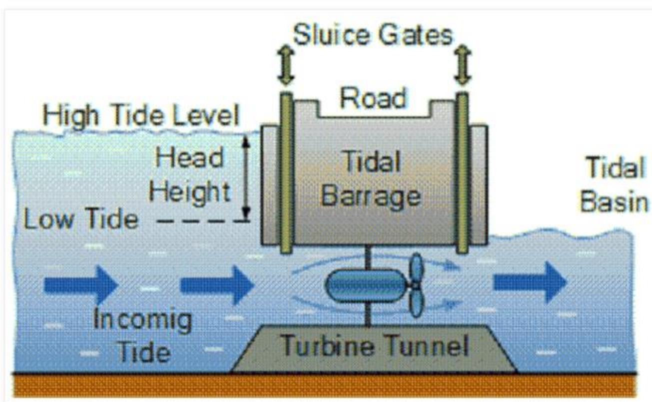


Fig. 2. Tidal Barrage Power Generation

3.1.2 Tidal turbines:

As Fig.3. These are turbines that are placed in the water and are turned by the flow of the tides. Tidal turbines can be either fixed to the seabed or floating [6].

Fig. 3. Tidal turbines power generation

3.2 Wave energy converters

Wave energy converters use the movement of waves to generate electricity. There are a number of different types of wave energy converters, but some of the most common include:

3.2.1 Point absorbers: In these Fig.4. are buoys or other floating structures that move up and down with the waves. The movement of the buoy is converted into electricity using a linear generator [7].

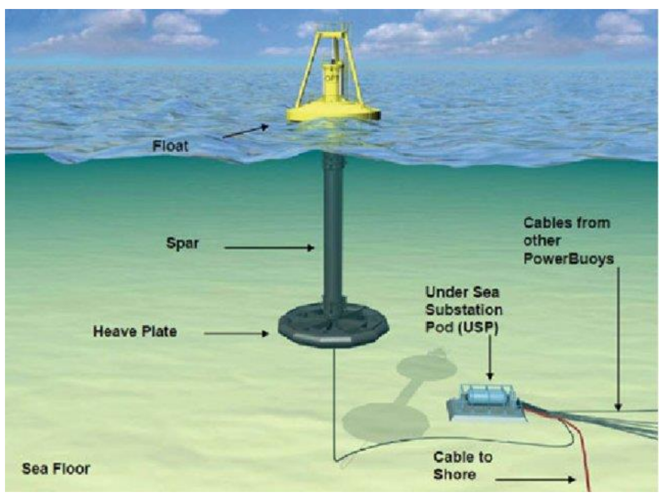


Fig.4. Point absorbers wave power generation

3.2.2 Attenuators: As this Fig.5. Attenuators are long, floating structures that are designed to absorb the energy of the waves. The energy of the waves is converted into electricity using a hydraulic system [8].

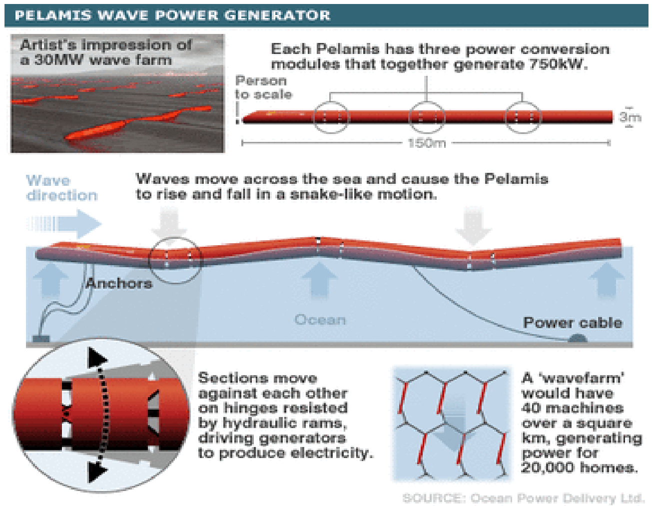


Fig.5. Attenuators wave power generation

3.2.3 Oscillating water columns (OWCs): These are chambers as Fig.6. that are partially submerged in the ocean. As the waves rise and fall, the air in the chamber is compressed and expanded. The compression and expansion of the air is used to turn a turbine, which generates electricity [9].

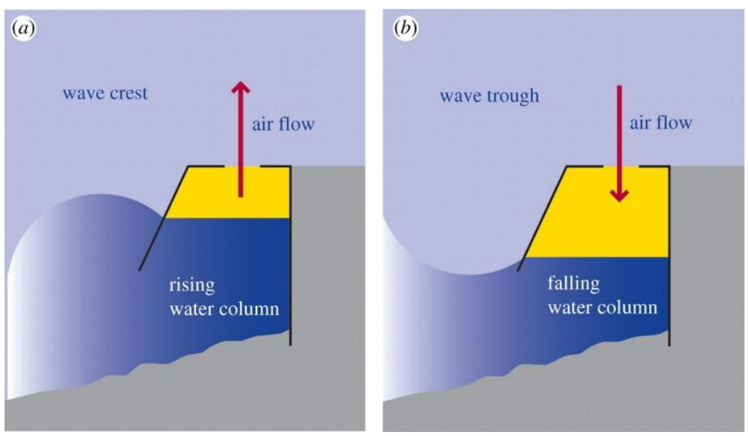


Fig. 6. Principle of OWC action.

3.2.4 Overtopping devices: These are structures as Fig.7. that allow waves to flow over them, filling a reservoir. The water in the reservoir is then released through a turbine, which generates electricity [10].

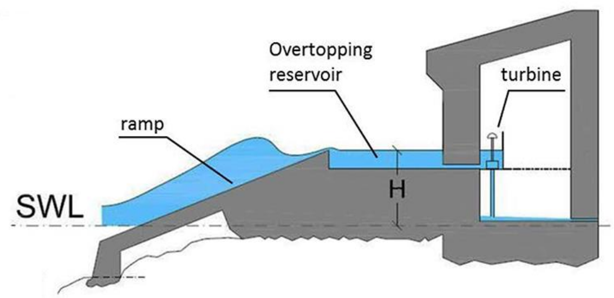


Fig. 7. OBREC illustration

3.2.5 Inverted pendulum devices: This Fig.8. is structures that are anchored to the seabed. As the waves rise and fall, the pendulum moves up and down. The movement of the pendulum is converted into electricity using a hydraulic system[11].

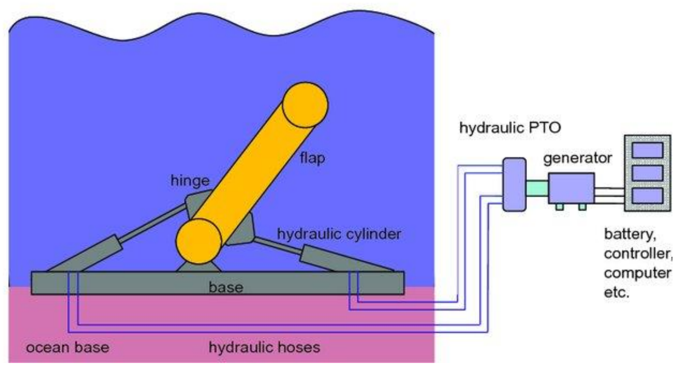


Fig. 8. A concept design of an 'Inverted Pendulum' wave energy converter (WEC) in the bottom wave areas of China

3.3. OTEC systems

OTEC systems use the difference in temperature between the surface of the ocean and the deeper ocean to generate electricity. OTEC systems use a heat exchanger to transfer heat from the warm surface water to the cold deep water. The heat is then used to drive a turbine, which generates electricity [12]. Fig.9. provides a visual representation of OTEC technology, which stands for Ocean Thermal Energy Conversion

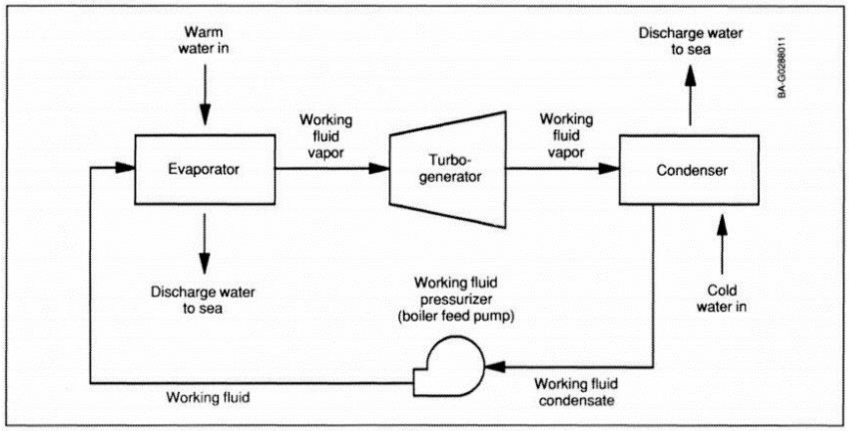


Fig.9. OTEC systems power generation

3.4. Salinity gradient Energy

Salinity gradient power technologies use the difference in salinity between seawater and freshwater to generate electricity. Salinity gradient power technologies use a membrane to separate the seawater and freshwater. The difference in salinity creates a pressure difference, which is used to drive a turbine, which generates electricity [13]. Fig.10. provide a visual representation of salinity gradient energy, also known as osmotic power or blue energy.

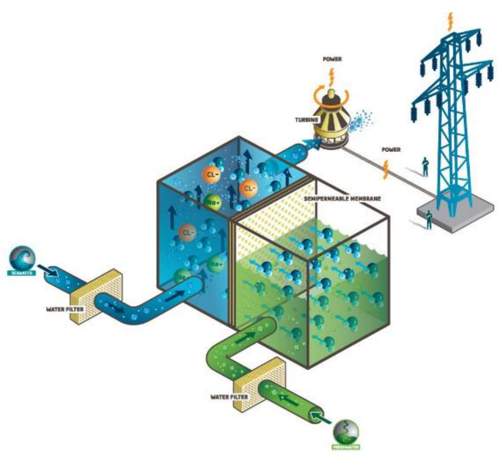


Fig.10. Salinity gradient power technology

4. ENVIRONMENTAL CONSIDERATIONS.

4.1. Impact of ocean energy on marine ecosystems.

There are marine renewable energy technologies are installed, they interact with and affect the surrounding marine environment in various ways. Depending on the specific technology, certain stressors or components of each device may affect marine animals and habitats, also called environmental receptors [14]. As ocean energy is a relatively new sector, regulators naturally have questions about the hypothetical impacts that installations could have on marine animals and habitats. Every project installing ocean energy devices in natural sea conditions includes measures to monitor the potential effects. Moreover, in 100% of cases, Environmental Impact Assessments (EIA) are carried out per European legislation (the EIA Directive and implementation). Despite this, there is not enough data today to be sure which, if any, of these hypothetical impacts pose a real risk. In some cases, this can hamper the consent of ocean energy projects [15]. Since ocean energy is in such an early phase, there is still a scarcity of scientific knowledge regarding its environmental effects. While some potential impacts are technology-specific, others are general and can be foreseen by considering the effects of existing marine activities. Fig.11 illustrates the potential stressors from the ocean energy systems considered here and from some other marine and coastal activities [16].

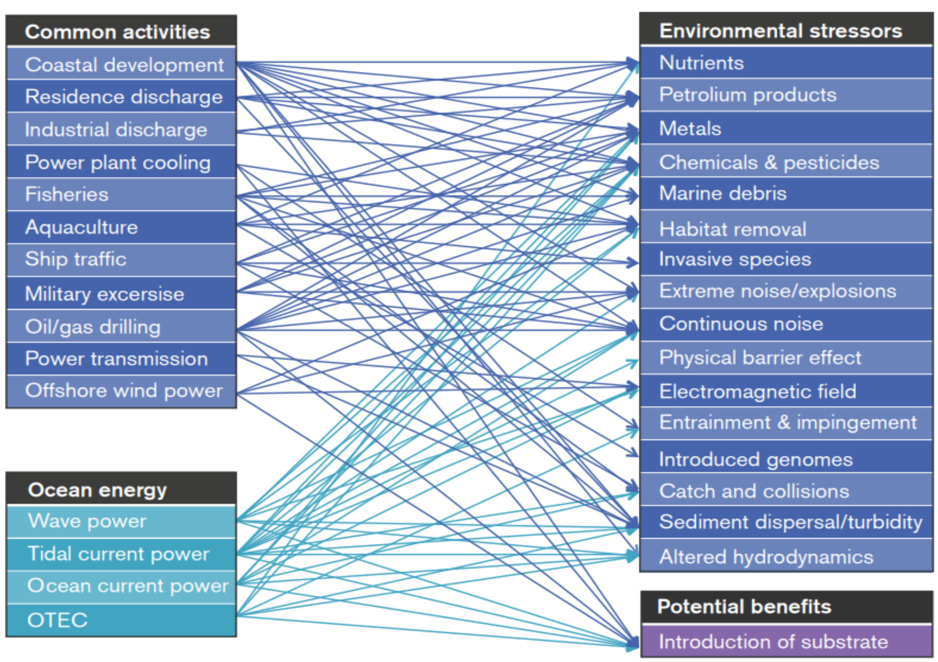


Fig.11. several concurrent activities stressing the maritime ecosystem.

Potential impacts on marine ecosystems:

(1) Collision risk with turbine blades.

(2) Effects of underwater noise on animals.

(3) Effects of electromagnetic fields (EMF) on animals.

(4) Changes in benthic and pelagic habitats.

(5) Changes in oceanographic processes; [17].

(1) Collision risk with turbine blades.

The collision of marine mammals, fish, and seabirds with the rotating blades or the stationary foundations of an ocean energy device is one of the most frequently referenced theoretical concerns in the deployment of ocean energy. This is a concern in areas with protected species that are more vulnerable to external factors [15]. To date, knowledge of the actual risk of collision for marine mammals, fish, and seabirds with turbines is limited because the frequency of occurrence and consequences are unknown. However, actual progress is being made to understand collision risk better, informed by research studies and post-installation monitoring of operational devices. Although there is no evidence to date to show that direct interactions with turbines will cause measurable harm to individual marine and riverine animals or populations, collision risk remains a crucial issue for the industry's future growth [17].

The severity of collision risk also depends on the type of ocean energy device—static or dynamic. ' Static' can qualify the device or its components, including foundations, power cables, or mooring lines located on the seafloor, mid-water column, or sea surface. Dynamic devices and components include rotating turbine blades or oscillating wave energy converters. They can be located above or below the sea surface. Experiences in field deployments of wave and tidal energy show that interactions with single static devices do not risk marine animals' well-being. The possibility of collision with dynamic ocean energy devices or their components is the most challenging barrier to permitting [15]. Research shows a shallow collision risk with wave energy converters, with no observed collision cases [15]. The research on tidal turbines shows no observed cases of marine mammals, fish, diving seabirds, or other marine animals ever colliding with an operational tidal turbine [15].

(2) Effects of underwater noise on animals.

For many marine animals, hearing is the main sense used to interact with the marine environment, either for communication, social interaction, orientation, predation, or evasion [15]. Anthropogenic sound in the marine environment may affect the way that many marine animals interact with their surroundings and may also affect communication, social interaction, orientation, predation, and evasion (Fig.12.) [17].

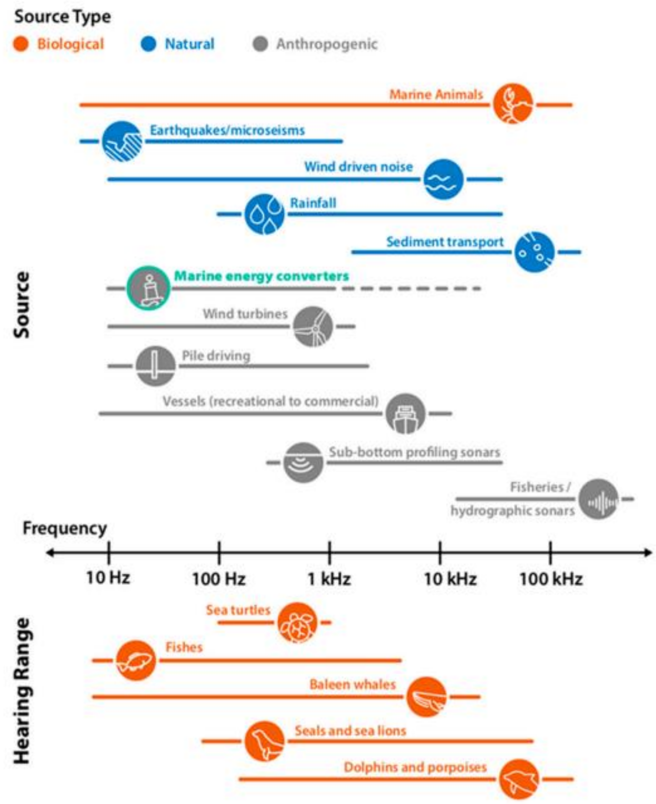


Fig.12. Marine animal hearing ranges and biological, natural, and anthropogenic noises.

The range of frequencies and amplitudes to which they are sensitive is wide and varies from species to species. Anthropogenic noise in the marine environment can potentially impact marine animals' hearing or ability to communicate and navigate with echolocation sounds [15]. Turbines and WECs both produce operational underwater noise, most commonly from the power take-off systems or generators, although some sound may be produced from mooring systems in the water column as well. Noise emissions from offshore construction activities, such as pile driving, may cause considerably more stress to marine animals [17]. Potential effects of anthropogenic noise sources on marine organisms are dependent on individual species' responses as well as characteristics of the noise source, including amplitude, frequency, and characteristics of how the sound propagates through seawater. A plausible range of physical impacts from high-intensity underwater sound includes a temporary or permanent reduction in hearing ability, damage to non-auditory tissues, irregular gas bubble formation in the tissues of fish and marine mammals, and neurotrauma (Gotz et al. 2009; Halvorsen et al. 2012; Oestman et al. 2009). The noise of this intensity is not anticipated from the operation of wave and tidal devices (Polagye, personal communication). Underwater noise may also result in behavioral changes such as avoidance of or attraction to the source and may also include masking—interference with communication, navigation, and detection of prey (Clark et al. 2009; Gotz et al. 2009) [14].

(3) Effects of electromagnetic fields (EMF) on animals.

Electromagnetic fields (EMFs) are magnetic fields created by moving electrically charged objects. EMFs exist naturally in the environment from sources such as the Earth's magnetic field and the energetic particles from the sun. In the marine environment, EMFs occur naturally as a result of the interaction between the conductivity of seawater, the rotation of the Earth, and the motion of tides or currents [15]. Fig. 13 shows how marine renewable energy (MRE) devices may affect receptor animals and their pathways [14].

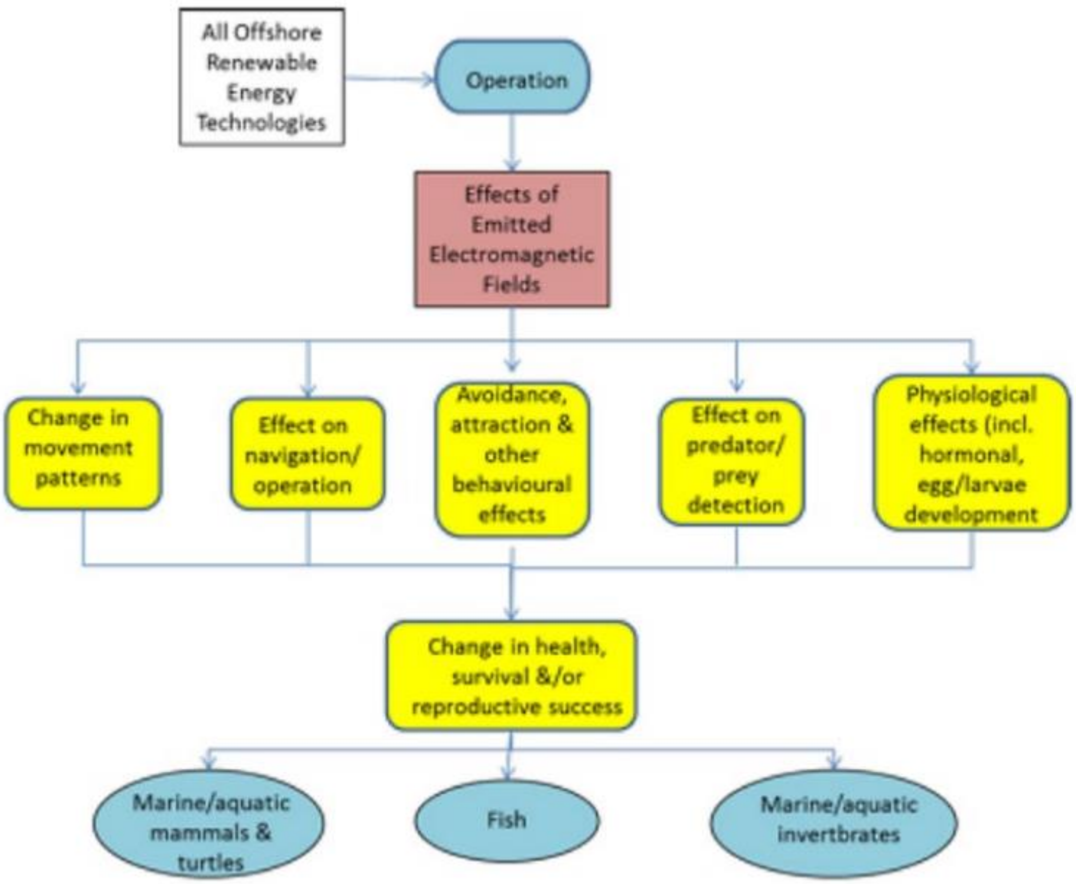


Fig.13. Pathways of Effect conceptual model for MRE device effects on receptor animals (redrawn from Isaacman and Daborn 2011)[14]

The main source of EMFs is cable connections between devices and export cables to shore. Many marine animals from different taxonomic groups can sense and respond to EMFs. They can detect electrical or magnetic fields with electro- or magnetoreceptors. Examples of these are sharks, lobsters, prawns, whales, dolphins, and marine turtles. A different magnetic field around the cable may attract animals to it or divert them from it [15]. The levels of EMF reported in many field and laboratory studies are much higher than those expected from MRE export cables, and the evidence to date suggests that the levels are unlikely to keep animals away from their preferred habitats or affect migration patterns [17]. To date, there is no evidence that EMFs from ocean energy installations have significant impacts on marine organisms. Studies have mainly focused on behavioral effects, showing that some sensitive species are attracted by EMFs. Significant biological impacts have not been detected [15]. More research and exposure assessments are needed to better understand the long-term impact of EMFs, as they are not readily available from studies in other industries [15].

(4) Changes in benthic and pelagic habitats.

The installation of devices on the seabed and the movements of turbines, anchor lines, and cables can have an impact on marine habitats. Sedimentation patterns, hydrodynamics, and seabed conditions can be altered, changing the benthic (the lowest level of a water body) ecosystem [15]. Adverse effects on the benthos that might be expected include loss of numbers and species of benthic organisms, degradation of habitat, and the creation of pathways for invasive species to become established [14]. The presence of these structures on the seabed or within the water column has the potential to alter species occurrence or abundance at a localized scale and may lead to the artificial aggregation of animals or changes in animal behavior. These changes may theoretically lead to indirect effects such as the recruitment of non-native invasive species or increases in biomass [17]. It is difficult to distinguish which effects are caused by the devices and which occur naturally because benthic communities are constantly changing natural ocean conditions. The studies conducted to date have not detected significant changes in benthic habitats, communities, or populations surrounding an ocean energy device [15].

(5) Changes in oceanographic processes.

The shift towards harnessing the power of the ocean brings about significant changes in the oceanographic systems, impacting various aspects of marine ecosystems. One of the key changes associated with marine renewable energy is the alteration of hydrodynamics within the vicinity of these installations. Offshore wind farms, for instance, introduce artificial structures that can modify the natural flow patterns of currents and tides. This alteration can lead to changes in sediment transport, nutrient distribution, and the overall circulation patterns of the area [18]. Furthermore, the construction and operation of marine renewable energy projects can generate underwater noise and vibration, which may have consequences for marine life. Marine mammals, such as whales and dolphins, rely on sound for communication, navigation, and prey detection. The increased noise levels from these installations can potentially disrupt these crucial acoustic behaviors [19]. Another significant aspect is the potential impact on the local biodiversity and ecosystem dynamics. Offshore wind farms may act as artificial reefs, providing new habitats for marine organisms. They can enhance the abundance of certain species and alter local species composition. Additionally, the deployment of turbines can affect the movement and migration patterns of fish, marine mammals, and seabirds, which can have cascading effects on the entire food web [20]. The introduction of marine renewable energy also brings the need for submarine cables to transmit the generated electricity to the shore. These cables can cause physical disturbances during their installation, potentially affecting benthic habitats and disrupting the sedimentary environment[21].

In summary, the development of marine renewable energy systems leads to significant changes in oceanographic systems. These changes encompass alterations in hydrodynamics, underwater noise, and vibration, impacts on biodiversity and ecosystem dynamics, as well as disturbances caused by submarine cables. It is crucial to assess and mitigate these effects to ensure the long-term sustainability and coexistence of marine renewable energy with marine ecosystems.

4.2 Mitigation strategies for environmental concerns.

Mitigation strategies for environmental concerns associated with ocean energy aim to minimize the potential negative impacts on marine ecosystems and biodiversity. These strategies encompass various aspects such as reducing underwater noise pollution, preventing habitat destruction and alteration, mitigating collision risks for marine organisms, managing impacts on fish populations, and monitoring and minimizing electromagnetic field (EMF) effects.

To mitigate underwater noise pollution, low-noise construction techniques and equipment are employed during the installation and maintenance of ocean energy devices. Device designs are optimized to reduce operational noise, and thorough environmental impact assessments are conducted to identify potential noise impacts on marine mammals [22].

Preventing habitat destruction and alteration involves careful site selection through marine spatial planning and conducting comprehensive environmental impact assessments. These assessments help identify sensitive habitats and inform mitigation measures to minimize seabed disturbance and hydrodynamic alterations caused by ocean energy installations [23].

Mitigating collision risks for marine organisms includes optimizing device layout and spacing to reduce the likelihood of collisions. Enhancing device visibility for marine animals and deploying acoustic deterrents further minimize the chances of interactions and collisions with ocean energy devices [24].

Managing potential impacts on fish populations involves implementing fish-friendly designs, such as fish-friendly turbine blades and intake/exclusion structures. Fish aggregation devices can also be deployed to minimize interactions with devices, and pre-and post-deployment monitoring programs help assess the effectiveness of mitigation measures [25].

To address electromagnetic field (EMF) effects, cable burial techniques are employed to reduce EMF emissions from submarine power cables. Optimizing cable routes to avoid sensitive areas and conducting regular monitoring of EMF levels help manage potential impacts on marine organisms [26].

By implementing these mitigation strategies, ocean energy projects can minimize their environmental footprint and promote the sustainable coexistence of clean energy generation with marine ecosystems.

5. CASE STUDIES

5.1 Successful Ocean energy projects worldwide

The initial wave energy converters (WECs) implemented included the 750 kW Pelamis, which utilized the oscillating bodies concept, and the 250 kW AWS, which also employed the oscillating bodies concept but in the form of a point absorber. These WECs were first deployed in Portugal in 2004. The Aquamarine Power Company has successfully implemented the initial iteration of the Oyster, a 315kW device, and the upgraded version, a grid-connected Oyster with a capacity of 800 kW. These deployments occurred at the Orkney site, specifically the European Marine Energy Center (EMEC), with the first installation completed in 2009 and the second in 2012 . The installation of near-shore 300 kW grid-connected Wave Roller units (consisting of three 100 kW WEC units) in Peniche, Portugal, has been carried out by the AW-Energy company.

Additionally, the construction of the initial commercial Wave Roller energy converter has been in progress since mid-2016 . The Basque Energy Board established the inaugural wave energy power plant in Mutriku. This plant utilizes the OWC wave energy conversion system, with each unit having a power capacity of 18.5 kW. The total installed capacity of the plant is 296 kW, achieved through the deployment of 16 WEC units. The Pico plant, which utilizes Oscillating Water Column (OWC) technology, has a power capacity of 400 kW and has been operational in the Azores, Portugal, for over ten years. Fig. 14 and 15 comprehensively depict several Wave Energy Converter (WEC) technologies that have been implemented in different projects across the globe as of 2018. Based on the provided data, it is evident that several wave energy converter (WEC) technologies, including Wave Roller, CETO 5&6, and Power Buoy, have achieved significant milestones. Nevertheless, to achieve the commercialization stage, it is imperative to decrease the development cost substantially [27].

Project Name (Lead Company)	WEC Technology	Capacity [MW]	Remark(s)
Carnegie Wave Energy Projects [61, 87]	CETO 5 	1	Located in Western Australia, In operation since January 2015, for commercial demonstration
	CETO 6 	Up to 3	Located in Western Australia, to be completed by 2020, for commercial demonstration
Port Fairy Pilot Wave Energy Project (BioPower Systems Pty Ltd) [87]	bioWAVE 	0.25	Located in Victoria, Australia, in operation since February 2016, for commercial demonstration

Fig. 14 Existing WECs technology in various projects by 2018

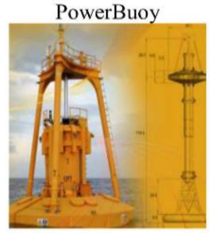
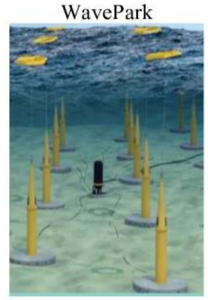
Project Name (Lead Company)	WEC Technology	Capacity [MW]	Remark(s)
Wattmor Wave Roller (Fortum, DCNS, AW-Energy)	WaveRoller 	1.5	Located in Brittany, France, started in 2013, for commercial demonstration
Mitsui Engineering & Shipbuilding Co. Ltd., Ocean Power Technologies, Inc.	PowerBuoy 	350	Located Kouzu, Tokyo, Japan, completed in 2017
Ocean Energy	StormBuoy 	40	Located in Norway, full-scale testing commenced in 2017
Seabased Wave Power & TC's Energy [88]	WavePark 	100	Located in Ada, Ghana For commercial scale (To be connected to Ghanaian National grid) Pilot project commenced in 2016 In May 2018, 14 MW connected to grid

Fig. 15 Available WECs technology employed in different projects by 2018

5.2 Challenges Existing Ocean Energy Projects Face

Development of Reliable and Cost-Effective Technologies: Developing dependable and cost-effective technologies is one of ocean energy projects' greatest obstacles. The harsh marine environment, including high waves, corrosive salinity, and extreme weather conditions, can present technical challenges and increase maintenance expenses.

Grid Connection and Infrastructure: It can be difficult to connect ocean energy projects to the electrical grid, especially if they are located in remote areas or far from extant infrastructure. Grid connection and transmission costs can be substantial and may necessitate substantial investments.

The environmental impact of ocean energy initiatives is a cause for concern. Certain technologies, such as tidal barrages, can potentially disrupt marine ecosystems, alter sediment transport, and alter the migration patterns of marine species. Minimizing and mitigating these impacts is essential for the development of ocean energy in a sustainable manner.

5.3 Lessons learned from case studies.

Policy Support and Enough Funding: Successful Ocean energy projects typically benefit from strong policy support and enough funding. The creation of advantageous market circumstances, the provision of financial incentives, and the support of research and development initiatives in the sector are all areas in which governments and regulatory organizations can play an important role.

Collaboration and exchanging knowledge are two of the most important aspects of advancing ocean energy technologies. Ocean energy technology stakeholders, researchers, and academic institutions must work together. It is possible to hasten the process of developing and deploying successful and cost-efficient solutions if expertise, best practices, and lessons learned are shared.

Site Evaluations and Environmental Impact Studies It is essential to the success of ocean energy projects to conduct in-depth site evaluations and environmental impact studies. A better understanding of the local marine circumstances, such as wave or tidal resources, the makeup of the seabed, and the ecological sensitivity of the area, can assist in reducing the potential for risk and improving project performance.

Testing and Invention of Technologies Continual testing and invention of ocean energy technologies are required to overcome technical hurdles and improve overall efficiency. To scale up and commercialization, iterative design processes, prototype testing, and demonstration projects can provide valuable data and insights.

Long-Term Planning and Stakeholder Engagement: Long-term planning is vital for minimizing delays and conflicts, including identifying suitable sites for development and evaluating potential conflicts with other marine operations. Stakeholder engagement is another critical aspect of long-term planning. Building trust, addressing concerns, and ensuring social acceptance of a project can be aided by early engagement with local communities, fishers, environmental groups, and other stakeholders.

6. ADVANTAGES AND CHALLENGES OF OCEAN ENERGY

6.1 Advantages of ocean energy:

Ocean energy offers numerous advantages as a renewable resource, making it an attractive option for sustainable power generation. Here are some key advantages:

1. **Abundance and Accessibility**
   Oceans cover over 70% of the Earth's surface, making them easily accessible for harnessing energy. Coastal regions have the advantage of proximity, allowing for efficient energy transmission to populated areas.
2. **Low Carbon Footprint**
   Ocean energy technologies produce minimal greenhouse gas emissions during operation. This characteristic contributes to mitigating climate change and reducing dependence on fossil fuels, fostering a cleaner and greener energy sector.
3. **Vast Energy Potential**
   The world's oceans possess an enormous energy potential. Tides, waves, currents, and thermal gradients can all be harnessed to generate power, offering a reliable and consistent energy source. While ocean energy technologies are still in their early stages of development, the theoretical capacity for harnessing energy from the ocean is substantial enough to meet the energy requirements of present and future generations.
4. **Climate change mitigation**
   Ocean energy has the potential to play a significant role in mitigating the adverse impacts of climate change. The International Energy Agency projects that on a global scale, the utilization of ocean energy could contribute to a substantial reduction of approximately 500 million tons of carbon emissions by 2050, stemming from the displacement of fossil fuel-based electricity generation [28].
5. **Predictable and stable energy**
   Compared to other renewable energy sources, it provides a higher degree of predictability and near-continuous electrical generation. This reliability makes ocean energy technologies well-suited for supporting and stabilizing electrical grids that incorporate intermittent renewable energy sources like solar and wind. By complementing these sources, ocean energy can contribute to a more reliable and resilient energy supply system [28].
6. **Offshore power**
   It has the capacity to deliver locally generated and reliable power to offshore industries, activities, and systems, including marine organism farming, navigation, and deployed ocean sensors. These sectors often rely on batteries that impose limitations on their range and effectiveness. By utilizing ocean energy, these offshore entities can access a sustainable and continuous power supply, enhancing their operational capabilities and reducing dependence on battery-based solutions [28].

7. **Support for coastal and rural island communities**
   Ocean energy has the potential to address the water and energy requirements of coastal and rural island communities, offering a locally derived power source to produce drinking water. By reducing dependence on expensive, carbon-emitting diesel generators that are susceptible to supply disruptions, ocean energy can enhance the sustainability and resilience of these communities. It provides an environmentally friendly and reliable alternative, enabling them to meet their energy needs while mitigating carbon dioxide emissions [28].
8. **Disaster recovery**
   It has the potential to assist in the recovery process following natural disasters in specific regions by offering resilient energy solutions to affected communities. For instance, incorporating ocean energy devices within breakwaters can ensure their protection during disasters, enabling them to provide essential services such as desalinated water and electricity to those communities. This capability not only enhances their resilience but also helps facilitate post-disaster recovery efforts in a sustainable and reliable manner [28].

6.2. Technical and economic challenges

Despite the promising advantages, ocean energy faces several technical and economic challenges that need to be addressed for widespread adoption. These challenges include:

1. **High costs**
   Ocean energy technologies are typically associated with higher costs compared to other renewable energy technologies, primarily due to the substantial expenses involved in installation, operation, and maintenance. Consequently, this cost disparity reinforces a perception of elevated risk associated with ocean energy projects, making it challenging to attract investors and secure insurance coverage. The perception of higher costs and risks poses obstacles to the widespread adoption and financial viability of ocean energy initiatives [28].
2. **Infrastructure**
   Ocean energy technologies encounter notable infrastructure challenges and limited development of supply chains. One prominent example is the substantial cost involved in connecting these devices to the electrical grid. Additionally, exposure to harsh weather conditions subjects certain components to significant wear and tear, necessitating robust maintenance strategies. The existing infrastructure gaps and vulnerability to environmental factors pose significant hurdles in the widespread deployment and long-term viability of ocean energy systems [28].
3. **Less Technology Development**
   Ocean energy technologies are still in the early stages of development, requiring further research and innovation to enhance their efficiency and reliability. Advancements in materials, engineering, and deployment techniques are essential to drive down costs and improve overall performance.

4. **Maintenance and Reliability**
   Maintaining and servicing ocean energy devices in challenging marine conditions is a complex task. Corrosion, biofouling, and extreme weather conditions pose operational challenges, necessitating robust maintenance strategies and reliable components to ensure optimal performance.
5. **Grid Integration**
   Integrating Ocean energy into existing power grids presents technical complexities. Matching the intermittent nature of certain ocean energy sources with grid demands requires advanced energy storage solutions and efficient grid management systems.
6. **Environmental effects**
   Ocean energy technologies present notable environmental risks, including potential collisions between marine life and underwater turbines, the generation of underwater sound, and alterations to habitats. However, further research is required to comprehensively evaluate the long-term impact of ocean energy technologies on the environment and marine wildlife. It is imperative to gain a deeper understanding of these effects to ensure the responsible and sustainable development of ocean energy, considering the preservation of marine ecosystems and wildlife [28].
7. **Regulatory challenges**
   Addressing the governance of ocean and coastal activities requires coordination among various federal and state entities. Consequently, the regulatory procedures involved can be time-consuming and costly [28].

6.3. Implementing strategies:

1. **Fund R&D**
   Most ocean energy technologies are either in the process of being tested or are already at the demonstration stage. It is crucial to encourage additional research and development by providing public funding or establishing an attractive environment for private investment to foster future advancements in this field [29].
2. **Increase awareness!**
   It is essential to raise public and policymaker awareness regarding the diverse range of ocean energy sources since the ocean has been largely neglected in the existing literature and renewable energy policies. Enhancing awareness requires improving the quality and accessibility of data on ocean energy resources [29].
3. **Rely on feed-in tariffs!**
   Countries blessed with abundant ocean energy resources can facilitate focused development by establishing dedicated feed-in tariffs for the different types of available ocean energy. This approach helps incentivize the growth of specific ocean energy technologies [29].

6.4. The Impact of Ocean Energy on Sri Lanka

Sri Lanka, an island nation in the Indian Ocean, has a coastline of 1,340 km and territorial waters covering approximately 21,500 km2. Its contiguous zone extends up to 24 nautical miles from the outer edge of the territorial zone, while the exclusive economic zone (EEZ) spans about 510,000 km2. With these characteristics, Sri Lanka has immense potential for harnessing ocean energy using five different technologies: tidal barrages, tidal/ocean currents, waves, temperature gradients, and salinity gradients [29].

6.4.1 Tidal Energy

As an island nation, Sri Lanka has significant potential for harnessing tidal energy. A tidal inlet is a coastal opening that allows for the exchange of water and nutrients. Tidal energy refers to the power harnessed from tides at these inlets. It is a dependable and sustainable form of energy. The high density of seawater, which is 800 times denser than air, makes tidal energy extraction a highly advantageous and reliable resource. Due to these benefits, tidal energy production has gained significant prominence as a crucial global energy source [31].

6.4.2 Ocean Thermal Energy

Sri Lanka, an island nation in the Indian Ocean with a coastline spanning 1,300 kilometers, has immense potential for ocean thermal energy conversion (OTEC) due to its tropical location. Research conducted by the National Institute of Oceanography and Marine Geology in Sri Lanka suggests that the country's OTEC potential exceeds 4,000 megawatts (MW), which is approximately 40% of its current power demand. The report highlights the western and southern beaches of Sri Lanka as having the most favorable conditions for OTEC development. However, despite these initiatives, OTEC implementation in Sri Lanka is still in its early stages and faces obstacles such as high initial investment costs and technical and environmental challenges associated with deploying these systems at sea [29].

6.4.3 Ocean Wave Energy

While Sri Lanka possesses a reliable and steady wave power resource, there are specific technical and environmental obstacles that require thorough evaluation. The wave energy industry is presently characterized by the development of multiple prototype devices. Nevertheless, additional research is essential to enhance the dependability and effectiveness of these devices, optimize energy extraction, and ensure cost-effectiveness. Identifying the most suitable device for a particular wave climate necessitates further investigation to advance the technology in this field [32].

So, Sri Lanka possesses significant potential for harnessing ocean energy, particularly wave, and tidal energy. The geographic position of Sri Lanka offers favorable conditions for leveraging maritime energy sources, which can substantially enhance the country's renewable energy mix. However, several challenges to overcome for the industry to expand include high initial costs, inadequate supportive policies, and weak regulatory frameworks. Despite these hurdles, Sri Lanka has demonstrated its commitment to renewable energy and is taking steps to create a supportive political environment for ocean energy development [29].

The future of ocean energy in Sri Lanka appears promising, considering its vast potential and dedication to a sustainable energy trajectory. With appropriate policies and incentives in place, ocean energy could serve as a sustainable and reliable electricity source, contributing to the country's energy security and sustainability objectives [29].

7. FUTURE OUTLOOK AND POTENTIAL

7.1. Emerging technologies and research developments

The world's oceans are an immense source of energy. Tides, waves, and temperature gradients offer a consistent and abundant supply of renewable energy that can be harnessed and converted into electricity. It is estimated that the global potential of ocean energy is several terawatts, making it a substantial contributor to the future energy mix.

Tidal energy technologies capture kinetic energy from the flow of tides, offering predictable and reliable power generation. Research is focused on improving efficiency and reducing the costs of tidal energy systems. One area of development is the use of innovative turbine designs, such as horizontal axis turbines with adjustable pitch blades, which can optimize energy capture across a range of tidal flow velocities.[33]

Ongoing research focuses on developing more efficient and reliable wave energy converters (WECs). Advantages designs, such as point absorbers and attenuators, are being investigated to improve energy capture and survivability in harsh marine conditions. Additionally, innovative control strategies, including resonance control and optimal power extraction algorithms, are being explored to enhance the performance of WECs. [34]

Ocean Thermal Energy Conversion (OTEC) utilizes the temperature difference between warm surface waters and cold deep waters to generate electricity. Ongoing research aims to improve the efficiency and economic viability of OTEC systems. Advanced heat exchangers and working fluids are being investigated to optimize energy conversion and reduce system size and costs. Additionally, efforts are being made to enhance cold water pipe designs and materials to minimize heat transfer losses during deep water intake.[35]

Hybrid systems that combine different ocean energy technologies are gaining attention for their potential to optimize energy production and grid integration. For example, combining wave and tidal energy systems in a hybrid array can leverage the complimentary characteristics of both resources and provide more stable and continuous power generation. Researchers are exploring optimal conFigurations, control strategies, and integration methods for such hybrid systems.[36]

7.2. Market potential and growth prospects

Ocean energy has significant market potential and growth prospects. The market size of ocean energy is projected to experience substantial growth in the coming years. According to a study by the International Renewable Energy Agency (IRENA), the technical potential of ocean energy exceeds 1000 GW globally, with wave and tidal energy accounting for the majority. [37] This represents a significant untapped resource that can contribute to the global energy mix.

Government around the world are recognizing the potential of ocean energy and implementing supportive policies to drive its development. Policy mechanisms such as feed-in tariffs, grants, and research funding, incentivize investments in ocean energy projects. For example, the European Union's Ocean Energy Strategic Roadmap sets ambitious targets for installed capacity, aiming for 100GW of ocean energy by 2050. [38] Such a policy support creates a conducive environment for market growth.

Commercial deployments of ocean energy devices are growing, indicating market maturity. Several wave and tidal energy projects have progressed from pilot and demonstration stages to grid-connected arrays. For instance, the MeyGen project in Scotland, one of the world's largest tidal stream arrays, has been successfully operating since 2016, supplying clean energy to the grid. [39] Such projects demonstrate the commercial viability and potential for large-scale deployments.

Technological advancements and innovation are driving cost reductions in ocean energy technologies, making them increasingly competitive. Improvements in device design, materials, and manufacturing processes are enhancing energy capture efficiency and reducing capital and operational costs. The levelized cost of electricity (LCOE) for ocean energy has been declining, signaling market competitiveness and growth potential [37]. The integration of offshore wind and wave energy systems offers synergistic benefits and market expansion opportunities. Combining these technologies in hybrid systems allows for efficient use of offshore infrastructure, grid connections, and resource utilization. Hybrid systems can leverage the strong winds and consistent waves in offshore environments, maximizing renewable energy production and optimizing project economics. [40]

Ocean energy projects have the potential to create economic opportunities and export markets. Counties with suitable ocean energy resources can become global leaders in technology development of new supply chains, job creation, and economic growth.

Integration of ocean energy into the energy mix holds great promise for achieving a sustainable and diversified energy portfolio. Ocean energy sources have complementary characteristics with other renewable energy sources, such as wind and solar power. While wind and solar energy are intermittent, ocean energy sources, particularly tidal energy, provide a more predictable and consistent power generation profile. This complementarity enables the integration of ocean energy with other renewables to ensure a stable and reliable energy supply. [41]

Tidal and ocean thermal energy conversion (OTEC) technologies have the potential to provide baseload power, contributing to grid stability. Unlike intermittent sources like wind and solar, tidal energy is highly predictable, as tides follows a regular and predictable pattern. By integrating tidal energy systems into the grid, a more balances and stable power supply can be achieved, reducing the need for backup fossil fuel power plants. [42]

7.3. Integration of ocean energy into the energy mix

Ocean energy systems can provide valuable grid services and ancillary benefits. The predictability and controllability of tidal and wave energy allow for the provision of ancillary services, such as frequency regulation and voltage support. Moreover, the spatial distribution of ocean energy resources, particularly offshore, can alleviate grid congestion and reduce transmission losses by locating power generation closer to demand centers. [43]

Ocean energy systems offer opportunities for decentralized power generation, particularly in coastal regions. Tidal and wave energy projects can be deployed near coastal communities, reducing transmission and distribution losses, and enhancing energy self-sufficiency. This decentralized approach can also enhance resilience and mitigate the vulnerability of energy supply in remote or island communities. [44]

The integration of ocean energy into the energy mix contributes to the global transition to a low-carbon economy. By replacing fossil fuel-based power generation, ocean energy systems help reduce greenhouse gas emissions and mitigate climate change. [45]

8. CONCLUSION

Ocean energy, also known as marine energy, is a prominent natural resource that could significantly contribute to global energy production. Due to the vast expanse of the ocean, it represents an immense and inexhaustible source of energy within a human lifespan. Harnessing ocean energy has been acknowledged to achieve zero carbon emissions during the energy generation process. Moreover, it has the potential to support numerous United Nations Sustainable Development Goals (SDGs) beyond those specifically related to affordable and clean energy (SDG 7) and climate action (SDG 13). Its impact extends to a wide range of SDGs, including SDG 1, SDG 2, SDG 5, SDG 6, SDG 8, SDG 9, SDG 14, and SDG 17. Therefore, it is crucial to capitalize on these natural resources to create a better world with a cleaner environment. There are five primary technologies employed to harness electrical energy from marine energy sources: tidal energy, wave energy, ocean thermal energy conversion (OTEC), salinity gradient energy, and ocean current energy. The history of ocean power plants can be traced back to the 1960s; however, this sector is still undergoing research and development. These five technologies employ various techniques, and a few successful projects have been implemented worldwide. As these technologies are still in the research and development phase, their environmental impact is closely monitored, and both advantages and disadvantages have been identified. Nevertheless, several challenges must be addressed to enable the widespread implementation of this reliable energy resource, particularly in island nations. However, there is a significant opportunity to generate electricity from this valuable renewable energy source to meet the global energy demand by enhancing these technologies and providing relevant financial and technical support to developing nations situated in coastal areas and islands.

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