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Review

A Comprehensive Review of Multi-Use Platforms for Renewable Energy and Aquaculture Integration

Alexandra Ionelia Manolache and Gabriel Andrei *

Department of Mechanical Engineering, Faculty of Engineering, "Dunarea de Jos" University of Galati, 47 Domneasca Street, 800008 Galati, Romania; alexandra.diaconita@ugal.ro
* Correspondence: gabriel.andrei@ugal.ro

Abstract: This review aims to find, classify, and discuss ongoing projects that fall into the category of multi-use platforms, concerning offshore energy exploitation and marine resource production, including aquaculture. The term multi-use platforms (MUPs) refer to areas that may accommodate multiple operations such as aquaculture, tourism, transportation, oil, or energy production. This research only examines the current situation of marine energy projects that entail the integration of either a single kind of renewable energy or other types of marine renewable energy, in conjunction with aquaculture. The particularity of this research consists in the exclusive choice of platforms that integrate two sources of renewable energy on a single platform. The study focuses on analyzing the projects set up over time on these platforms, all of which include aquaculture. The state of the art in MUPs for offshore applications was examined to generate the review. We devised a methodical search approach aiming to find relevant material from various academic fields. During this phase, we looked to understand as much as we could about MUPs, including their design, the nature of these projects, what kinds of projects they can include, how they integrate renewable energy sources, and whether aquaculture facilities can be put together. To preserve scientific integrity and guarantee the inclusion of relevant research, a search strategy was formulated. The bibliographic study was through critical analysis, and at the end, significant conclusions were drawn concerning the development of multi-use platforms.

Keywords: multi-use platforms; renewable energy; aquaculture; offshore

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1. Introduction

When it comes to the vast oceans and intricate coastlines, the desire for progress by humans often comes into conflict with the need to safeguard the environment [1]. Because of the unrelenting use of finite resources, the global economy has had a long-lasting effect on the ecosystems of our planet, resulting in a number of environmental challenges [2]. The danger of climate change, produced by the continual emission of greenhouse gases from industrial activity, transportation, and changes in land use [3,4], is one of the primary problems that people are concerned about.

In view of the current environmental predicament, the necessity for swift and decisive action is more critical than it has ever been before. International agreements such as the Paris Agreement [5] and the Kyoto Protocol have made it easier for people all around the world to work together to combat climate change and advance sustainable development. Nevertheless, in light of the persistent rise in emissions and the intensifying effects of climate change, it is becoming more apparent that there is an urgent need for solutions that are both courageous and imaginative.

When these challenges are taken into consideration, the exploitation of marine and coastal resources has evolved into something that is both a blessing and a source of conflict. The generation of energy, maritime transportation, fishing, tourism, and aquaculture are only some of the businesses that struggle for limited space and resources. This competition usually results in the destruction of sensitive marine ecosystems. The idea of Integrated Maritime Policy provides a framework for striking a balance between economic development and environmental protection [6]. This is necessary to navigate the complex web of competing interests that exist in the maritime industry.

The primary areas of concentration for this endeavor to strike a balance are aquaculture and renewable energy. Not only has the fast spread of marine aquaculture brought about a transformation in the global fish business, but it also has the potential to supply sustainable food supplies for a population that is rising all over the globe. As an additional point of interest, the rapid advancement of renewable energy technology, which includes offshore wind farms as well as wave and tidal energy converters, provides a mechanism to accomplish decarbonization in the maritime industry and reduce reliance on fossil fuels.

Nevertheless, to fully use the possibilities of these companies, it is necessary to overcome a number of technical, economic, and regulatory constraints [7]. Although offshore aquaculture facilities offer advantages in terms of their capacity to cultivate and make optimal use of resources on a vast scale, they need innovative solutions to overcome the problems that they present in terms of logistics and to guarantee the environmental sustainability of their operations [8,9]. Similar to the previous example, the introduction of renewable energy sources into maritime infrastructure requires careful planning and a financial commitment to grid infrastructure, energy storage technology, and transmission technology.

Multi-use platforms (MUPs) have the potential to bring about a revolution in the maritime industry regarding the production and use of energy [10]. These types of systems, whether they are installed on floating platforms or integrated with aquaculture facilities, can supply dependable and robust power for marine operations because they are able to utilize the complementing characteristics of renewable energy sources [11]. When it comes to satisfying the energy requirements of offshore installations, the inclusion of wind, solar, wave, and tidal energy sources provides MUPs with a solution that is both flexible and adaptable (Figure 1). This solution also helps to reduce dependency on fossil fuels and mitigate harmful effects on the environment [12].

Figure 1. Graphic representation of all studied elements that can coexist in a MUP: aquaculture, offshore wind energy, offshore solar energy, marine energy represented by a tidal energy converter (for the elaboration of this image, the vectors were taken from [13]).

In this context, understanding the intricate dynamics of marine spatial planning, renewable energy integration, and the promise of hybrid energy systems becomes imperative. By elucidating these complex phenomena, we aim to chart a course toward a more sustainable and prosperous future for our planet's oceans and coastlines.

1.1. Scope, Objectives, and Structure of the Review

The term multi-use platforms (MUPs) encompass several characteristics, as it refers to an area that may accommodate multiple operations such as aquaculture, tourism, transportation, oil, or energy production. This research only examines the concept of marine energy projects that entail the integration of either a single kind of renewable energy or many forms of renewable energy offshore, in conjunction with aquaculture. The peculiarity of this research lies in its exclusion of various kinds of platforms, namely those that integrate two sources of renewable energy on a single platform. Instead, the study focuses on analyzing the projects established over time on these platforms, all of which include aquaculture.

1.2. Search Strategy

The review study assessed offshore MUPs' current situation. Methodical searching was used to identify relevant academic literature. During this phase, we sought to understand as much as we could about MUPs, including their design, the nature of these projects, what kinds of projects they can include, how they integrate renewable energy sources, and whether aquaculture facilities can be located together. To preserve scientific integrity and guarantee the inclusion of relevant re-search, the search strategy was created.

The first step in the documentation plan was to choose keywords or key phrases pertinent to our subject. Keywords like "offshore", "renewable energy", "aquaculture", "colocation", "multifunctional platforms", and "hybrid platforms" were utilized.

Keyword search strings were used to seek relevant scientific databases. Customizing search queries captured MUPs' structural design, current projects, ecological integration, and economic qualities. These search strings ensured a balanced approach to research in engineering, environmental science, and economics.

The search technique was implemented using several reliable databases, guaranteeing thorough coverage of peer-reviewed literature. The broad indexing of scientific publications and conference proceedings pertinent to offshore engineering, renewable energy, and marine sciences makes databases like Web of Science, Scopus, PubMed, Engineering Village (Compendex, Inspec), and IEEE Xplore desirable.

Search results were limited to peer-reviewed, English-language papers over the last decade. These filters prioritize current research and scientific rigor in language.

Specific MUP data, such as active projects, completed assessments, and other relevant observations, were obtained using tailored search methods. This strategy improved keyword combinations for concrete data: project details and analytical research. Our search parameters were targeted to gather as much information as possible on MUP design, functioning, environmental implications, and technological advances.

In order to select potential publications for a wide approach, the second stage included looking over the citations from the significant articles that had been found.

Searching scientific materials and undertaking statistical analysis to assess MUPs' renewable energy utilization was the third step. The number of active farms, capacity factors, efficiency of energy production, and technical developments were among the important criteria that were the subject of these assessments.

Data were collected from press announcements, project prototype websites, and other sources at ongoing project sites, which did not necessarily follow scientific norms. For completeness and academic trustworthiness, scientific literature that usually examines or evaluates these projects was still sought.

A visual representation of the complete process is shown in Figure 2 to enhance comprehension of the processes involved in the preparation of the review article.

Figure 2. Summary of the systematic literature review protocol.

2. Current State of the Renewable Energies and Aquaculture That Can Be Integrated in MUPs

2.1. Offshore Wind Energy

The offshore wind energy business plays a crucial role in worldwide energy strategy due to increasing energy needs, the global transition to renewable energy sources, and the usually greater wind speeds found offshore compared to onshore. This industry has experienced significant growth over the last twenty years [14]. Over the last two decades, there has been a significant growth in this business [15]. The offshore wind capacity has increased significantly, starting with a modest 0.06 GW in 1996–2000 and reaching 18 GW in 2018. It then doubled to 36 GW at the beginning of 2020 and further surged to an impressive 73 GW by the end of 2023. Offshore wind farms are strategically located across Europe, Asia, and America. Figure 3, derived from data in the 4C Offshore database [16], indicates that as of mid-2024, over 333 offshore wind farms have been authorized. Among them, 60.2% are situated in Asia, 38.9% in Europe, and a meager 0.9% in America. The United States is the only country in the Americas that has operating offshore wind farms, highlighting its growing importance in this dynamic sector. Of the total 333 wind farms, China has the largest number of offshore wind farms, with about 145 installations. The United Kingdom comes second with 43 farms, followed by Vietnam with 29. Currently, a total of 19 nations have successfully established and are actively operating offshore wind farms. Among them, 13 are located in Europe and 5 in Asia.

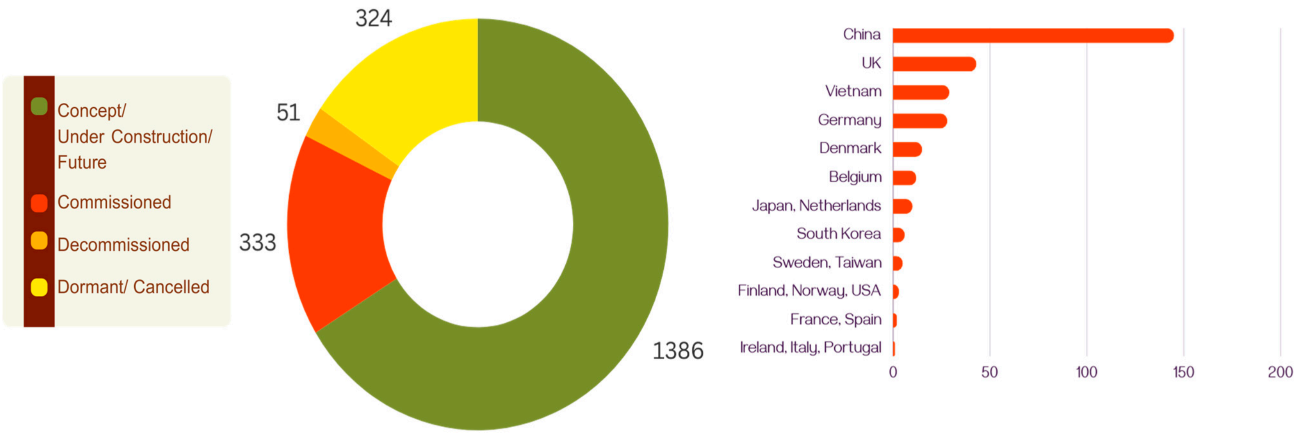

Figure 3. Number and status of offshore wind farms.

Beyond the commissioned offshore wind farms, there exists a substantial number of projects, totaling 1386, currently in various stages such as construction, conceptualization, or earmarked for future development. Additionally, there is an equally large number of projects, akin to those commissioned, that have been canceled but may potentially be revived in the future. Furthermore, Figure 3 illustrates a rising trend in decommissioned offshore wind farms, reflecting industry dynamics and lifecycle management considerations. These observations underscore the dynamic nature of offshore wind energy development, characterized by ongoing project evolution and strategic decision-making influenced by economic, environmental, and regulatory factors.

From the analysis of the 333 offshore wind farms in operation, the largest is the Hornsea Project, located in the North Sea near Yorkshire, England, and developed by Ørsted. The project is divided into multiple phases: Hornsea Project One, completed with an installed capacity of 1.2 GW, was among the world's largest offshore wind farms upon its finalization. Hornsea Project Two, also completed, boasts an installed capacity of 1.4 GW, further solidifying the project's global leadership in offshore wind energy. Hornsea Project Three, with a planned capacity of 2.4 GW, is set to significantly expand the project's capacity and impact. Additionally, Hornsea Project Four, planned for future development, will add an impressive 2.6 GW to the project's total capacity. This ambitious initiative plays a crucial role in the United Kingdom's renewable energy strategies, aiming to provide clean electricity to millions of homes and contribute substantially to reducing carbon emissions.

The biggest offshore wind farm project in terms of total capacity to be completed later is the Dogger Bank Wind Farm, which was established by Equinor and SSE Renewables. It has been divided into three phases: Dogger Bank A and B, with installed capacities of 1.2 GW each, have already been completed, reinforcing its standing as an important contributor to global offshore wind energy capacity. Dogger Bank C, with a planned capacity of 1.2 GW, will come afterwards. As such, when fully operational, it is anticipated that other schemes' total capacity will exceed that of Dogger Bank Wind Farm, thereby emphasizing its leading role in advancing clean energy objectives and mitigating climate change in this area and beyond.

Offshore wind turbine farms consist of many crucial components to effectively harness wind energy. The components include wind turbines, foundations, electrical infrastructure, substations, and transmission networks. The electrical infrastructure, including subsea cables and offshore substations, is essential for connecting the produced electricity to the onshore grid, ensuring the effective distribution of energy [17]. Scientific research on offshore wind farms' electrical infrastructure focuses on many critical aspects. These include the tasks of designing and optimizing subsea cable networks, ensuring the dependability and upkeep of electrical components, and incorporating renewable energy into already established power grids [18]. Research often investigates the thermal performance and insulation characteristics of subsea cables to improve their efficiency and longevity. Research also investigates novel materials and methods to enhance the durability of electrical systems in challenging maritime environments. Furthermore, there is significant focus on the development of sophisticated monitoring and diagnostic instruments to forecast and avert malfunctions, ensuring continuous power transmission.

Notwithstanding progress, there are still several obstacles in the electrical infrastructure of offshore wind farms that require more investigation. Because subsea cables may experience breakdowns in hostile maritime environments, their reliability and durability are critical. Research should prioritize the development of durable materials and resilient coatings. Efficient electrical design optimization, involving the use of high-voltage direct current (HVDC) technology, is crucial for reducing energy losses and enhancing cost-efficiency. To ensure optimal performance in different settings, it is essential to tackle thermal management by using sophisticated modeling techniques and innovative cooling technology.

The integration of offshore wind energy into the onshore system continues to be complex. It is crucial to develop more advanced grid management systems, energy storage solutions, and technologies that can balance the grid to provide a consistent supply of power. Real-time monitoring and predictive maintenance systems, including artificial intelligence and machine learning, are essential for anticipating faults and minimizing downtime. Conducting targeted research in these areas may improve the efficiency, dependability, and cost-effectiveness of offshore wind farms, thereby encouraging their wider use as a sustainable energy solution.

The wind turbines and their foundations are the most essential components of offshore wind farms [19]. The wind turbine, including the rotor, nacelle, and tower, is responsible for converting kinetic wind energy into electrical energy. Wind turbines have seen substantial advancements over time. Presently, there are 43 manufacturers of wind turbines, with Siemens and Vestas being the most prominent. The CSSC Haizhuang H260-18 MW (Figure 4) has emerged as the most powerful operating wind turbine, demonstrating a significant improvement in power output over the first offshore wind turbine ever built. Technological progress in turbines enables them to efficiently harness larger amounts of wind energy, resulting in increased power generation. This innovation leads to improved efficiency and lower prices per megawatt-hour, making offshore wind energy more competitive compared to conventional energy sources.

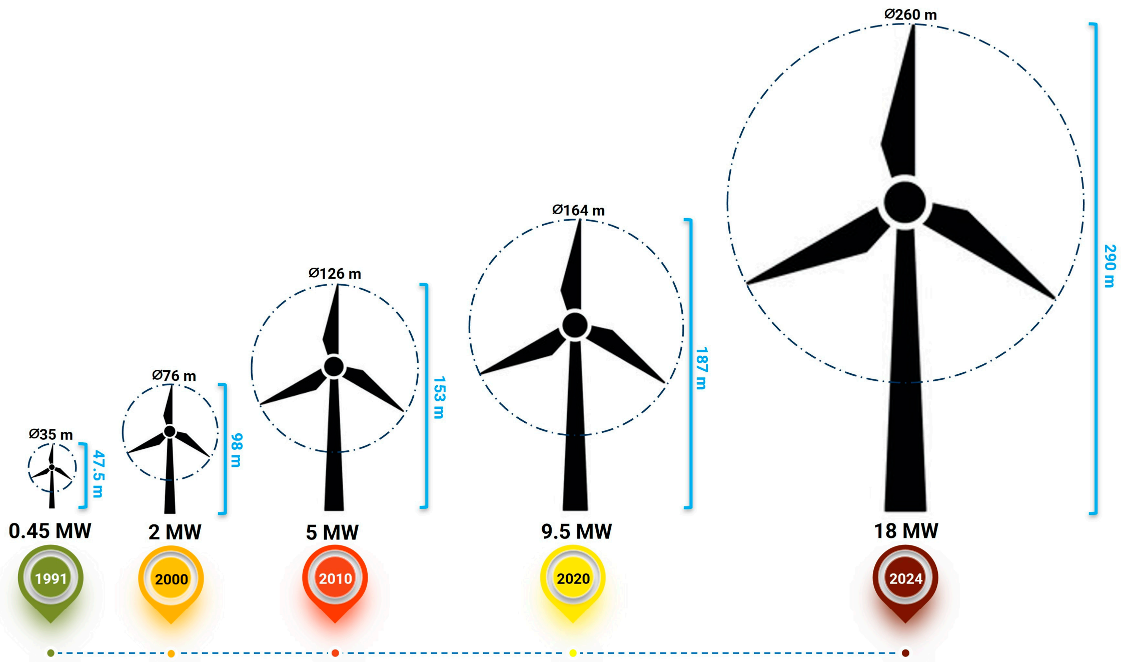

Figure 4. Advancement over time of the wind turbine's general characteristics.

Scientific studies on wind turbines often focus on improving aerodynamic efficiency, structural integrity, and material durability. Research on rotor blade design aims to enhance performance by optimizing blade shape and materials to withstand harsh offshore conditions. Studies also investigate the reliability and maintenance of nacelle components, including the gearbox and generator, to minimize downtime and extend operational lifespans. Advances in tower design are explored to improve resilience against dynamic loading and fatigue caused by wind and wave interactions. To reduce operational costs, we need further research to develop more resilient materials and predictive maintenance technologies using artificial intelligence. Enhancing energy conversion efficiency through advanced rotor designs and improving nacelle component reliability remain critical areas. Additionally, the trend toward larger turbines necessitates studies on the impacts of increased size on structural integrity and maintenance requirements.

Figure 5 shows that the monopile type of foundation is the most commonly employed, followed by the high-rise pile head, which is the preferred type in China. China's coastal regions contain most of the high-rise pile cap foundations. Tripod and floating barge foundations are among the least utilized types; the latter is less common due to its intricate structure.

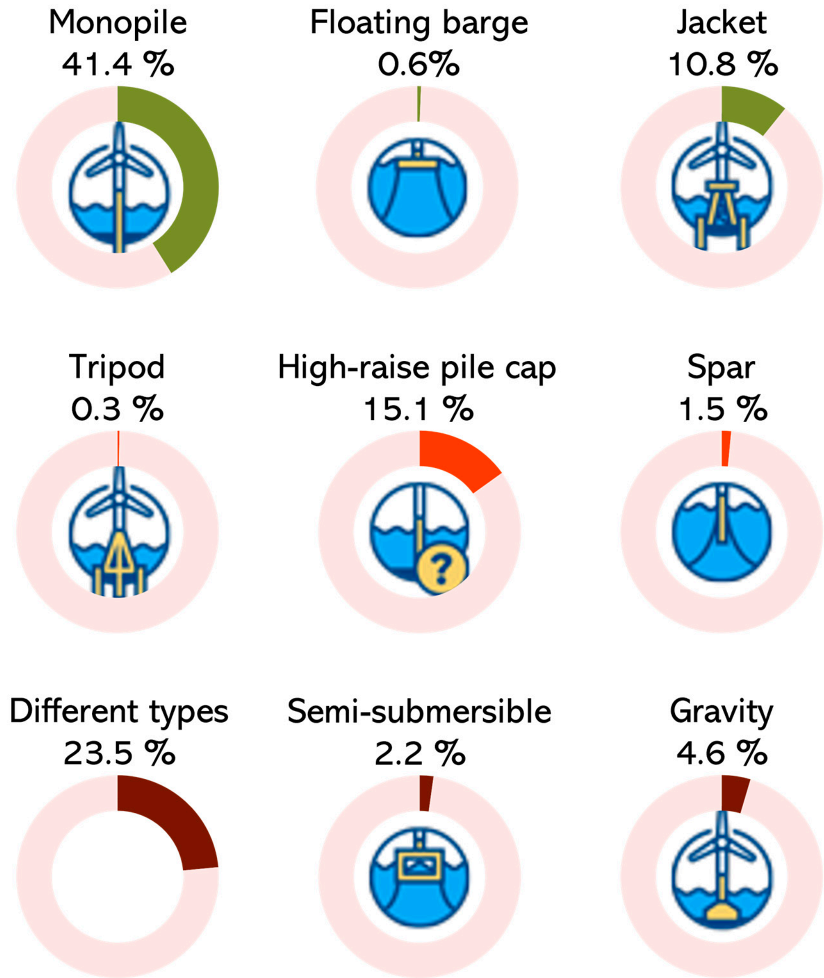

Figure 5. Types of foundations and the percentage they occupy in operational wind farms.

Foundations, whether fixed-bottom or floating, provide essential stability and support at varying sea depths. Fixed-bottom foundations include monopiles, suitable for waters up to 30 m deep; jacket structures for depths up to 50 m; tripod foundations for intermediate depths; and gravity-based foundations for shallow to moderate depths. Floating foundations, such as semi-submersible platforms, spar-buoy structures, and Tension Leg Platforms (TLPs), are designed for deep-water locations where fixed-bottom foundations are not feasible. Research typically addresses the structural dynamics and geotechnical interactions with the seabed. Fixed-bottom foundations, such as monopiles and jacket structures, are studied for their load-bearing capacity and resistance to corrosion and fatigue. Floating foundations, like semi-submersible platforms and TLPs, require studies on mooring systems and dynamic stability in deep waters. Innovative materials and construction techniques are being explored to enhance the durability and cost-effectiveness of these foundations.

Despite prior research, issues with the foundations of offshore wind turbines persist. Important factors to consider are the long-term durability of floating platforms in harsh maritime conditions, ongoing challenges with corrosion in fixed-bottom foundations, the environmental impact of installation and maintenance, and the necessity for cost-effective design improvements. To facilitate the sustainable growth of offshore wind energy, further research is required to develop state-of-the-art materials, enhance technological solutions, and elevate environmental requirements.

2.2. Offshore Solar Energy

Floating photovoltaic (FPV) systems have emerged as an essential technology in the field of renewable energy. This is because they compete with typical solar installations that are located on land. These systems provide a variety of benefits that just cannot be ignored on account of their existence. These systems, which make use of bodies of water such as lakes, reservoirs, and oceans as platforms, can generate solar energy in an efficient manner. This is achieved using these systems. The implementation of this technique not only enhances the efficiency with which land is used, but also brings about several particular advantages and difficulties that are essential for carrying out an in-depth inquiry and analysis.

The increased amount of energy output that FPV systems create is a huge benefit when compared to solar arrays that are situated on the ground. This is because FPV systems generate more energy than land-based solar arrays. Due to the several aspects that contribute to this potential, it has been shown via study that FPV systems have the potential to provide a bigger energy output of around 10–20% [20]. All of these factors contribute to this potential. There are several benefits associated with the cooling impact that water bodies have on solar panels. One of these benefits is that it helps to maintain suitable operating temperatures, which are essential for solar panels to work correctly. This results in an improvement in both the overall performance of the panels as well as the efficiency with which they operate inside the system. Natural cooling helps to reduce the risk of thermal deterioration and enhances the durability of photovoltaic (PV) modules. This, in turn, eventually results in an increase in the quantity of energy that is generated throughout the course of the modules' lifetimes of operation.

The total installed capacity of FPV systems throughout the world is anticipated to have reached around 5.7 gigawatts (GW) by the time the year 2022 comes to a close [21]. A variety of countries throughout the continents of Asia, Europe, and the Americas have been responsible for the construction of notable installations. The capacity of the system is expected to exceed seven gigawatts by the year 2023, as shown by the predictions. FPV technology has been developed to the point that China has established itself as a leading country in the area. The nation is home to a variety of enormous facilities that, when combined, generate hundreds of megawatts of power. The Zhejiang province project, which has a capacity of 550 megawatts [22], is generally regarded to be one of the most significant FPV projects that are now taking place anywhere in the globe. China is dedicated to increasing its infrastructure for renewable energy sources, as seen by the country's use of cutting-edge technologies.

For the purpose of ensuring that the platform continues to be stable, photovoltaic panels are first installed on buoyant platforms, and then they are effectively fastened and knotted. The solar farm that is being described here is referred to as a floating solar farm. The farm is outfitted with electrical infrastructure, which includes inverters, cabling, and monitoring and control systems, with the intention of offering aid to those who need it. These characteristics have been thoroughly investigated and designed in such a manner as to maximize the quantity of energy that is gathered, enhance efficiency, and guarantee a connection that is seamless with the electrical grid. Furthermore, the existence of support infrastructure, including control rooms and power substations, is necessary for the purpose of monitoring and maintaining the operations of the system. This is to ensure that the system continues to operate properly.

As the current stage of development for these systems is still in its early phases, a full study of the potential advantages and obstacles connected with FPV systems is required. It is essential to get a comprehensive knowledge of these challenges to enhance the viability and longevity of photovoltaic (PV) equipment that is installed offshore. Table 1 gives a quick evaluation of the benefits and drawbacks associated with FPV systems.

Table 1. Advantages and disadvantages of floating solar panel farms.

Advantages	Disadvantages
• Reduces evaporation of surface water, conserving water resources [20,23,24].	• Technological challenges in offshore/marine environments [25–27].
• Reduces wave formation, minimizing erosion of reservoir banks [28].	• Requires durable materials to withstand water, salinity, humidity, and environmental stress [29,30].
• Decreases reflectivity of water, increasing solar radiation absorption [31].	• Prone to corrosion and potential induced degradation in seawater environments [32].
• Cooling effect from the water surface increases efficiency of PV modules and cables. Evaporative cooling extends the lifespan and energy gain of PV modules [33,34].	• Marine organisms attach to submerged structures, increasing maintenance needs [35].
• Declining costs of PV panels and installation [36,37].	• Potential issues like bird attraction and destruction of habitats (birds, green marshes) [38,39].
• Reduces photosynthesis and algae growth, improving water quality [40].	• Potential for freshwater pollution from panels and structures [41].
• Operates in less dusty environments than ground-based systems [42].	• Complex and long structures are difficult to accommodate and maintain [43].
• Converts unused non-commercial water into profitable solar PV power plants [44].	• Susceptible to tides, storms, ocean waves, cyclones, and tsunamis [26].
	• Light and waterproof materials for floating systems can be expensive [45].

The table summarizes the most current findings from research and provides a summary of the findings. Besides displaying the issues that have been researched over a period of time, the table also illustrates the advantages and downsides of the scenario. In other words, it contains both strengths and weaknesses. However, since this subject is still in its infancy, there is a considerable need for further study to be carried out on it. Some industries do not have sufficient resources for research and have not been assigned the proper amount of priority. This illustrates the need to do ongoing research to find solutions to these limitations and guarantee that the technology behind FPV is developed in a complete way.

An important aspect to mention is related to the first offshore aquaculture farm, Ocean Farm 1, which was installed in Norway [46,47]. This project measures 110 m in width and 68 m in height with a cubic volume of 250,000. This represents the largest project of its kind and pushes the limits of aquaculture to new limits, representing a pioneer for new innovations in the industry.

2.3. Marine Energy

Marine energy, also known as ocean energy, is a rapidly growing sector in the world of renewable energy sources. It utilizes the immense, unexplored capabilities of the Earth's oceans to produce electricity through natural occurrences like waves, tides, currents, and temperature variations. Marine energy is a tempting route for scientific research and technical innovation, despite the fact that it is still in its early phases compared to more established renewable technologies such as wind and solar [48,49]. The following are the various types of marine energy: wave energy, tidal energy, ocean thermal energy, ocean current energy, and osmotic energy (Figure 6).

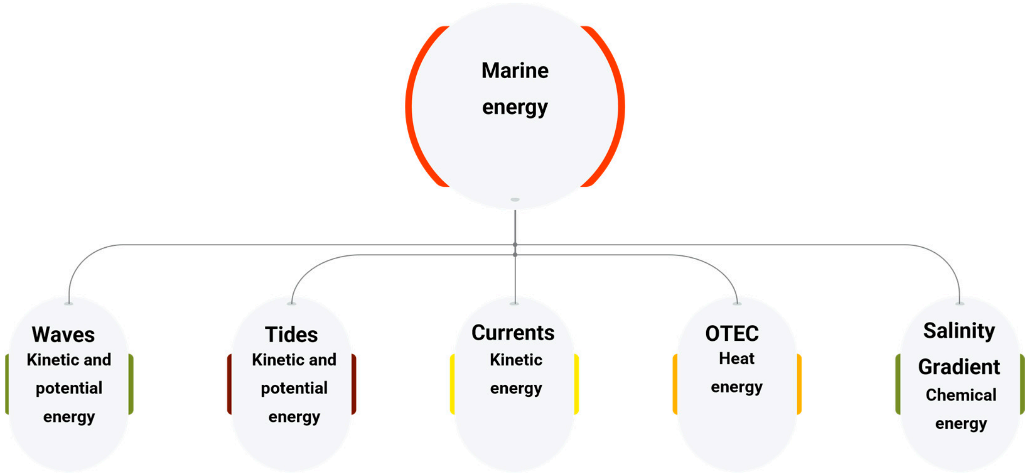

Figure 6. Marine energy classification.

The installed marine energy capacity worldwide as of early 2023 was 523 MW, with South Korea and France accounting for most of this capacity [50]. Important undertakings consist of:

- Operating since November 1966, the 240 MW La Rance Tidal Power Station in France produces about 600 GWh of electricity annually [51];
- Operating since August 2011, the Sihwa Lake Tidal Power Station in South Korea is the largest tidal power plant in the world, with a capacity of 254 MW and an annual output of 550 GWh [52].

As mentioned earlier, there are numerous types of marine energy which use various technologies, some of which are illustrated in Figure 7. Due to extra-tropical storms, wave power is concentrated between latitudes 30° and 60° in both hemispheres and has enormous energy potential. Wave-activated bodies (WABs), oscillating water columns (OWC), overtopping devices, and other novel ideas are examples of wave energy conversion technologies [49].

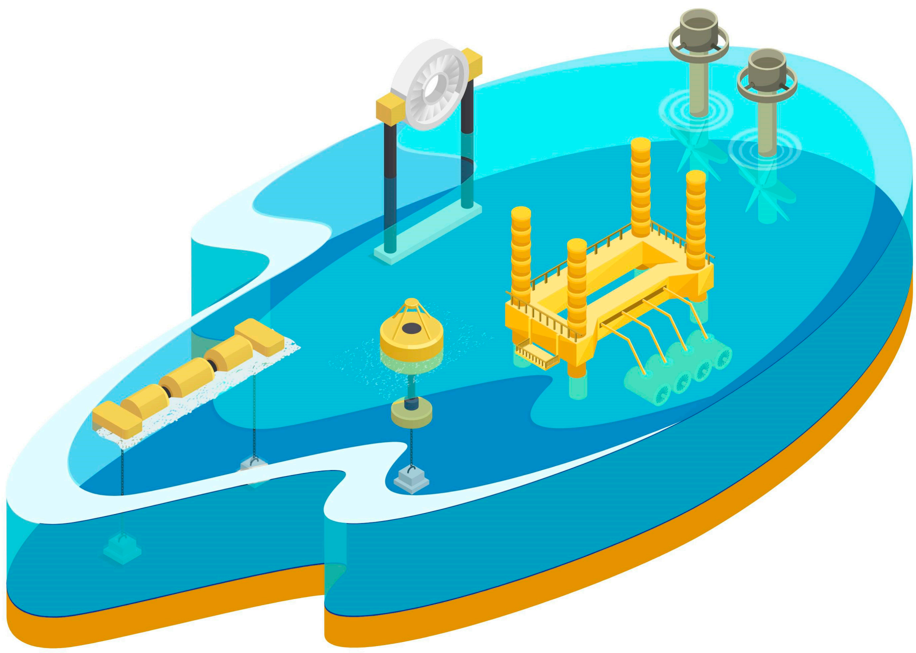

Figure 7. Different technologies used to harvest marine energy: tidal turbines, attenuators, and point absorbers (for the elaboration of this image, the vectors were taken from [13]).

Using tidal ranges—commonly found in places like the Bay of Fundy in Canada and the Severn River Estuary in the United Kingdom—tidal power captures the energy they produce. By using flood, ebb, and two-way generation schemes, tidal energy uses barrages and turbines to harness the kinetic energy of tidal movements [53].

Utilizing the kinetic energy from stable currents like the Kuroshio Current and Gulf Stream, ocean current power generates electricity. In Japan, Vietnam, Taiwan, and the Philippines, innovative technologies such as tidal kites and horizontal axis turbines are being developed. To effectively capture kinetic energy, ocean current energy conversion technologies include oscillating hydrofoils, horizontal and vertical axis turbines, and novel ideas like tidal kites [54].

The tropics have a tremendous deal of potential for ocean thermal energy conversion (OTEC), which makes use of temperature differences between surface and deep seawater. By adjusting closed, open, and hybrid cycles to various thermal gradients, OTEC systems make it easier to generate electricity from variations in ocean water temperature [55].

The energy released when mixing freshwater and saltwater is harnessed by salinity gradient power. Utilizing global river discharges as potential energy sources, salinity gradient energy conversion techniques such as pressure-retarded osmosis (PRO) and reverse electrodialysis (RED), use osmotic pressure differences to generate electricity [56,57].

The challenges faced by marine energy underscore the complex landscape it must navigate within the broader realm of renewable energy. Marine energy is still largely untapped and carries financial risks, even though it has the potential to generate consistent power from natural sources like waves and tides. There are various reasons why the technology is being adopted at a slower pace in comparison to well-established renewable energy sources like solar and wind power. There are several factors to consider, such as the substantial upfront costs, the complex technical requirements in difficult marine conditions, and the various regulatory hurdles. Maritime energy presents unique challenges and can be expensive, necessitating reliable grid connections and storage solutions to address its intermittent nature. Despite ongoing developments and experimental initiatives, the sector still has a lot of progress to make in terms of operational track record and scalability compared to solar and wind energy. To fully unlock the potential of marine energy as a valuable addition to renewable energy portfolios worldwide, it is essential to prioritize research, innovation, and the development of supportive regulatory frameworks. Significant amounts of money will be needed for them. These steps are crucial for tackling the current challenges and promoting sustainable growth in this sector.

Based on available data up to 2010, the total installed capacity was a mere 250 MW [58,59], with the majority of 240 MW being generated by the farm constructed in 1966. The capacity of the tidal farm reached 503 MW in 2011 [50], with the completion of the biggest tidal farm. Since then, there have been no notable improvements in capacity. Between 2020 and 2023, there will be a period of no growth or development in this industry. Marine energy, formerly seen as a very promising renewable energy source, is now lacking in appeal owing to many unfavorable issues affecting the business.

A tabular summary (Table 2) was created to enhance the linkage of the renewable energy examined in the preceding three sections.

Table 2. Comparative summary of offshore renewable energy technologies.

Aspect	Offshore Wind Energy	Offshore Solar Energy	Marine Energy
Growth	Significant growth: from 0.06 GW in 2000 to 73 GW by 2023, with over 333 wind farms globally. Major regions include Asia, Europe, and the U.S.	Growing technology, with 5.7 GW installed globally by 2022. China's FPV systems are particularly prominent.	Early-stage sector with 523 MW installed by 2023, largely in South Korea and France. Historically slower growth compared to wind and solar.
Leading countries	China, the United Kingdom, Vietnam, and the U.S. are major players in offshore wind energy.	China leads with massive FPV projects like the Zhejiang province's 550 MW project.	South Korea and France dominate with large tidal power stations (e.g., Sihwa Lake, La Rance).
Key technologies	Wind turbines (e.g., monopiles, floating platforms), subsea cables, HVDC technology for power transmission, advanced rotor designs.	Floating photovoltaic (FPV) systems, buoyant platforms, and natural water cooling to improve efficiency.	Wave energy converters, tidal turbines, oscillating water columns, and ocean thermal energy conversion (OTEC) systems.
Challenges	Issues include subsea cable durability, corrosion, foundation stability, grid integration, and high capital investment. Research is needed on materials for harsh marine environments.	Corrosion, material degradation in marine environments, and maintenance challenges from marine organisms. Also, complex structures and potential environmental impacts such as pollution and habitat disruption.	High upfront costs, operational risks, regulatory barriers, and technological complexity in harnessing wave, tidal, and thermal energy. Lack of scalability and intermittent energy generation remain significant challenges.
Future potential	Plans for major expansions with projects like Hornsea and Dogger Bank wind farms. Ongoing innovations in turbine size, foundation design, and real-time monitoring systems to improve efficiency and longevity.	Promising growth with ongoing innovations in platform stability, durability, and cost-effectiveness. Natural cooling effects of water could continue to enhance solar energy efficiency and module lifespan.	Potential to contribute significant energy, but financial investment, regulatory support, and technological innovations are needed to unlock broader development, especially in wave and ocean thermal energy.
Environmental benefits	Reduction of carbon emissions and support for renewable energy goals.	Reduces land use for solar farms, conserves water by reducing evaporation and improves water quality by limiting photosynthesis and algae growth.	Harnesses renewable ocean energy with minimal greenhouse gas emissions, offering a consistent and powerful energy source.

2.4. Aquaculture

Aquaculture, the controlled farming of aquatic organisms such as fish, shellfish, and seaweed, has rapidly expanded to meet the growing global demand for seafood. As an industry, it contributes over 50% of the world's seafood supply [60], producing approximately 94.4 million tons of fish annually as of 2022, according to the Food and Agriculture Organization (FAO) [61]. This sector supports millions of jobs and generates significant economic benefits, particularly in developing countries where fish is a major source of protein. Advanced technologies and innovative practices, such as Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA), have been developed to enhance efficiency and sustainability. Despite these advancements, the industry faces critical challenges that must be addressed to ensure its long-term viability and minimal environmental impact.

By examining various aquaculture farm designs, we can observe that a variety of issues need to be resolved, including those pertaining to habitat disruption and nutrient pollution that are typically present in open-water farming [62], integrated multi-trophic aquaculture (IMTA) [63], and traditional pond systems [64]. Furthermore, issues with capital have been identified in recirculating aquaculture systems (RAS) [65], and managerial challenges, particularly in IMTA, exist. Offshore aquaculture, conducted in deeper ocean waters, reduces competition for coastal land and benefits from strong water flow, yet faces high costs and technological challenges [66,67]. These designs collectively highlight the industry's adaptability and the need for continued research and innovation to mitigate environmental impacts and ensure sustainable growth.

2.5. Assessment of Coastal Areas for Aquaculture and Renewable Energy Integration

In the preceding sections, we have discussed each kind of renewable energy and aquaculture individually, which are the specific subjects of this review article. The objective of this part is to individually examine the resources of each kind of renewable energy, as well as the capacity for exploitation in aquaculture and the leading nations in this sector. The goal is to identify important regions where these characteristics may be combined in MUPs.

In 2023, China achieved a remarkable feat by surpassing all other countries in aquaculture production, reaching an impressive output of 58.12 million metric tons [68]. Additional notable producers include Indonesia with a production of 14.6 million metric tons [69], India with 9.4 million metric tons [70], and Vietnam with 4.7 million metric tons [69]. South Korea, Chile, Norway, Thailand, and the Philippines are also notable suppliers [71]. These nations have both flourishing aquaculture industries and significant renewable energy resources in their nearby waterways that might be combined with aquaculture operations.

When studying the potential of wave energy, an important factor to consider is the average yearly energy flow. This value might range from 0 to more than 120 kW/m in various regions around the world [72,73]. The southern coastal regions of Australia have significant intensities, ranging from 15 to over 90 kW/m in areas further from the coast, while the coastal regions of Chile may surpass 90 kW/m [72]. The coastal areas of Ireland and Scotland in Europe have substantial potential, with values exceeding 60 kW/m [74]. The Black Sea region has an average wave energy flow of up to 7 kW/m [75], while the Baltic Sea shows a maximum of 8 kW/m [76]. These regions possess significant but comparatively smaller potential for wave energy. The Mediterranean Sea has a maximum power density of 10.2 kW/m [77], but the coastal regions of Japan and China have larger potentials, reaching values of up to 36 kW/m [78] and 20 kW/m [79], respectively.

The Global Wind Atlas data [80] reveal that the coastal areas of New Zealand and Chile have the highest mean power density at a height of 100 m for offshore wind energy, reaching up to 2280 W/m^2 and 2750 W/m^2, respectively. Additional regions of notable importance include the Newfoundland Sea, where solar irradiance reaches around 1850 W/m^2, and the North Sea, renowned for its considerable use of offshore wind energy, with an estimated solar irradiance of 1600 W/m^2. The coastal areas of China and Japan have significant solar energy potential, with China receiving an average solar irradiance of 1200 W/m^2 and Japan receiving 1050 W/m^2. Indonesia and Thailand, on the other hand, have lower wind power densities, reaching a maximum of 300 W/m^2.

For the evaluation of solar resources, the parameter called solar radiation was used [81]. In the North Sea, this parameter reaches its maximum value at roughly 160 W/m^2 [82], decreasing toward the Baltic Sea to around 140 W/m^2 [83] or even lower. The Black Sea has a peak value of 150 W/m^2, while the Mediterranean Sea attains around 220 W/m^2 [83]. The coastal regions of South Korea and Indonesia have maximum values of up to 200 W/m^2 [81], whereas certain coastal locations in China and Japan have lower levels of around 150 and 160 W/m^2 [81], respectively. On the other hand, the coastal areas of India have greater values that go over 225 W/m^2 [81], while the northwestern coastline region of Australia stands out with an estimated value of 264 W/m^2 [81].

By analyzing these results and various studies, a close correlation was observed between certain sources of renewable energy and aquaculture. For example, the area of the Mediterranean Sea where the exploitation of both wave and wind energy is possible [84]. Similar studies were also carried out in the North Sea, after which the feasibility of integrating such systems was established [82,85,86]. Further research in Taiwan's coastline region confirmed the possibility of combining such projects [87].

3. Analyzing Projects and Designs in Offshore MUPs

3.1. Real Hybrid Renewable Energy Projects with Aquaculture

In this section, a series of projects that have reached the concept phase, have been tested, or are fully functional will be presented and then summarized in Table 3 at the end of the subchapter. These projects present all the previously analyzed fields—offshore wind energy, offshore solar energy, wave energy, and aquaculture. Each project presents unique qualities and innovative designs that aim to create efficient environments for the exploitation of multiple resources.

The Guoneng Sharing project [88–90] is the first functional project involving floating offshore wind energy with aquaculture, developed by China Energy Longyuan Power and is located in Zhoushan, Zhejiang, and now being towed to Pingtan, Fujian. Each floating structure of the project involves a semi-submersible type of foundation on which a 4 MW wind turbine is placed, as along with flexible modular solar panels. Between the three pillars placed in a triangular shape is a deep-sea fishing net cage with a capacity of approximately 10,000 cubic meters, and its main purpose is yellow croaker fishing.

The development of this project involved a meticulous analysis that included universities and design companies, forming a team dedicated to the design of the floating structure. This developed team aimed to identify a suitable location, conduct structural hydrodynamic analysis, and optimize the design to withstand the marine environment in the China area. The project is estimated to produce approximately 96,000 kWh of electricity at maximum capacity.

The Ming Yu No. 1 project [91–93] represents another large-scale project developed and designed by Mingyang Smart Energy. It is the first offshore project to combine offshore wind power with aquaculture, having recently been installed at the Mingyang Qingzhou 4 offshore wind farm in the South China Sea. The main foundation used is the jacket type, and it is the first of this type to host both a wind turbine and fishing infrastructure, along with an intelligent management system for feeding the fish, cleaning the nets, and collecting the fish, but it is also equipped with a real-time monitoring system. This type of project is developed to withstand typhoons of class 17. The turbines used for this project differ and have capacities of 11 MW, 12 MW, and 16.6 MW. In the case of this project, the nets used have a capacity of 5000 cubic meters and can accommodate approximately 150,000 fish. The main goal of this project is not only to optimize the use of marine space but also to contribute to the economy of renewable energy projects.

The Blue Growth Farm (BGF) [94,95] was a pioneering EU Horizon 2020 project, running from June 2018 to January 2022, involving 14 partners across five EU countries. Notable participants included RINA Consulting, the University of Strathclyde, and TECNALIA. BGF aimed to create an environmentally friendly open sea farming platform that integrates aquaculture and renewable energy. Key features included a modular floating platform with a central fish farming pool, space for a 10 MW wind turbine, and wave energy converters, using cost-effective, corrosion-resistant concrete caisson modules. Challenges addressed during the project included efficient design, scaled prototype construction, and developing a viable business model. Outcomes encompassed a comprehensive design assessment and successful scaled prototype operation, proving both technical and economic feasibility. Despite its innovative approach, BGF faced scrutiny due to technical and logistical challenges of integrating multiple functions on a single platform and ensuring environmental sustainability in open sea conditions. The project concluded by highlighting the need for ongoing research and stakeholder collaboration to fully realize the potential of MUPs.

The AquaWind project [96], co-funded by the European Maritime, Fisheries, and Aquaculture Fund (EMFAF), aims to demonstrate a practical multi-use (MU) integrated solution for offshore renewable energy development in the Atlantic Sea Basin. Led by the Government of the Canary Islands in Spain (GOBCAN), AquaWind integrates a floating wind turbine prototype (W2Power) with an innovative aquaculture setup. W2Power is an innovative adaptation of mature offshore technologies tailored for deep-water offshore wind applications, enabling a rated capacity of 12 MW on a single floating foundation [97,98]. This includes custom-designed fish cages with advanced net materials, digital monitoring systems, and the cultivation of various fish species and marine organisms, such as seaweed and shellfish. Aligned with the European Commission's guidelines for sustainable EU aquaculture (2021–2030), AquaWind promotes inclusive resource sharing among stakeholders from industry, academia, regional authorities, and civil society. Positioned as a Flagship project for the Atlantic Basin, AquaWind aims to showcase the combined benefits of offshore renewable energy and aquaculture. This approach not only addresses challenges such as food scarcity and climate change adaptation but also contributes to economic development and job creation in coastal communities. Through its prototype development, AquaWind seeks to validate the technical feasibility, economic viability, and environmental sustainability of its MU platform. By demonstrating the scalability of integrating wind energy generation with aquaculture, AquaWind exemplifies how collaborative innovation can offer sustainable solutions to complex societal challenges.

The Solar Oyster Production System (SOPS) [99,100], co-founded by Solar Oysters LLC and Blue Oyster Environmental (BOE), aims to revolutionize oyster farming by integrating solar power with aquaculture. Capable of producing up to 200,000 oysters in a 0.02-acre space, SOPS significantly outperforms traditional methods in efficiency. The system features a floating platform with solar panels that power rotating ladders, which cycle oysters through varying water conditions for even exposure to salinity, temperature, dissolved oxygen, and phytoplankton, while out-of-water exposure reduces biofouling. This innovative design reduces labor and enhances oyster yield, supporting both consumption and restoration markets. Set to operate on Hoopers Island Oyster Company's lease in 2024, the SOPS prototype will validate its technical feasibility, economic viability, and environmental sustainability. By advancing aquaculture technology and promoting sustainable practices, the collaboration with BOE aims to contribute to the restoration of the Chesapeake Bay's oyster population and support the local marine ecosystem.

Haiwei-2 [101] is a pioneering semi-submersible aquaculture platform developed by China, designed to operate in offshore waters. This platform integrates aquaculture capabilities with renewable energy through the installation of solar panels. These solar panels primarily power the platform's operations, enhancing its sustainability by reducing reliance on conventional energy sources. It is important to note that while Haiwei-2 incorporates solar energy for its internal operations, it does not export excess energy, distinguishing it from hybrid platforms designed to export surplus renewable energy to the grid. This innovative approach allows Haiwei-2 to optimize its environmental footprint while supporting efficient aquaculture practices in deeper offshore environments.

The Penghu semi-submersible aquaculture platform [102,103], developed by the Guangzhou Institute of Energy Conversion (GIEC) of the Chinese Academy of Sciences, represents a pioneering integration of Sharp Eagle Wave Energy Converter technology with offshore aquaculture. Deployed in Zhuhai, China, in June 2019, Penghu combines 60 kW Sharp Eagle WECs and 60 kW solar photovoltaic units to address challenges faced by traditional aquaculture cages, such as energy supply limitations and insufficient space for modern farming equipment. With a 15,000 m^3 internal pool for finfish farming and expansive platform area for aquaculture equipment, Penghu demonstrates GIEC's commitment to advancing sustainable aquaculture practices. Its deployment at the Guangdong Wanshan Islands Wave Energy Demonstration Zone and subsequent relocation to a nearby fish farm illustrate its adaptability and effectiveness in real-world marine environments. GIEC continues to refine Penghu's design through rigorous numerical and experimental analyses, ensuring its reliability and efficiency under varying environmental conditions. As GIEC progresses with further development efforts, Penghu stands as a pioneering example of integrating renewable energy and aquaculture to promote food security and environmental sustainability in coastal regions.

The TROPOS project [104,105], developed by a collaborative effort involving academic institutions, industry partners, and policymakers, has focused its study primarily on exploring the feasibility and benefits of modular MUPs. The project's area of interest includes diverse geographic locations, encompassing sites in Gran Canaria and Taiwan, where specific case studies were conducted to assess the viability and impacts of MUPs. The project has pioneered innovative designs and advanced technological solutions for these platforms, emphasizing integration across renewable energy, aquaculture, maritime transport, and leisure activities. Among the conceptual designs explored, the Green & Blue concept has emerged prominently due to its potential to optimize synergies between renewable energy and aquaculture while minimizing environmental impact.

Through innovative designs and advanced technological solutions, TROPOS has proposed modular platforms capable of operating in deep waters, where conventional fixed platforms are impractical. This flexibility not only expands the scope of offshore resource exploitation but also minimizes spatial footprint and environmental impact, setting a precedent for future offshore developments. The project's methodologies, such as Geographic Information System (GIS) decision support tools and environmental monitoring strategies, have been instrumental in evaluating site-specific scenarios and assessing their socio-economic and environmental impacts comprehensively. These tools not only aid in optimal platform placement but also in mitigating negative effects through informed decision-making.

However, despite these advancements, TROPOS remains in the conceptual stage, primarily offering theoretical models and simulations rather than real-world implementations. The critical next step lies in transitioning these innovative concepts into pilot-scale deployments. Real-world testing is essential to validate technological feasibility, assess practical challenges, and refine operational strategies. Moreover, while TROPOS has made strides in identifying potential regulatory and legislative gaps for MUPs, there is a pressing need for more robust frameworks. Clear guidelines and standards are crucial to navigating regulatory complexities and ensuring compliance with environmental protections and safety measures [106].

TROPOS represents a significant leap forward in offshore platform design and integration, particularly with its Green & Blue concept, the project must pivot towards practical deployments to substantiate its theoretical findings. Addressing regulatory challenges and refining operational frameworks will be pivotal in realizing the full potential of MUPs, ensuring they deliver on their promise of sustainable energy solutions while safeguarding marine ecosystems and supporting local economies.

The Hex Box project [107,108] is another concept project developed by Ocean Aquafarm; it combines offshore wind energy with aquaculture. The assembly is provided with a floating steel structure that can host three wind turbines and is equipped with a double net to provide high protection against the difficult marine environment, but also to prevent fish escape. The nets range in size from 70 to 90 m deep. In addition, the whole hybrid platform is provided with a remote winch operation system. The project is designed to withstand difficult environments and is divided into three categories: Hex Box standard is designed to withstand waves with a significant wave height of up to 10 m, Hex Box harsh for a significant wave height of up to 12.5 m, and Hex Box exposed for a significant wave height of over 12.5 m. The project aims to enhance the sustainability and efficiency of offshore fish farming by leveraging deep-sea aquaculture techniques, contributing to a secure and profitable aquaculture industry.

The WSA concept, developed as part of innovative offshore engineering, integrates multiple functionalities aimed at maximizing marine space utilization and resource efficiency. This hybrid system includes a robust steel fishing cage with a vast internal volume exceeding 300,000 m^3, designed not only for aquaculture but also to support four vertical-axis wind turbines (VAWTs) and a solar array. The fishing cage, constructed with steel components including rectangular pontoons and cylindrical columns, features copper alloy nets known for their superior stiffness and reduced drag compared to traditional materials. This structural advantage allows for substantial fishery capacity, equivalent to 600 HDPE cages, enhancing both productivity and economic viability.

The WSA concept [109] diverges significantly from conventional MUPs discussed previously. In contrast to predominant designs utilizing Horizontal Axis Wind Turbines (HAWTs), the WSA integrates three VAWTs, marking a departure in technological approach. VAWTs are characterized by simpler mechanics, quieter operation, and omnidirectional wind capture capability without necessitating complex yaw systems. However, they historically exhibit lower efficiency and heightened maintenance demands, particularly in the challenging conditions of offshore environments where wind conditions vary unpredictably and can be severe. VAWTs are strategically mounted on the fishing cage to optimize wind energy capture. These turbines are complemented by a solar array fixed on a truss structure above the cage, designed to minimize wind loads and ensure ample sunlight penetration for aquaculture health. Together, these renewable energy components contribute significantly to the operational self-sufficiency of the system, providing ample electricity to support both offshore activities and local communities.

Critical to the operational stability of the WSA is its mooring system, employing catenary lines for station keeping in water depths ranging from 100 m to 200 m. This choice mitigates wave-frequency loads and reduces installation and maintenance costs compared to polyester lines, aligning with industry standards for offshore platform stability. Furthermore, the modular construction and assembly process of the WSA allow for cost-effective fabrication and pre-assembly onshore, minimizing logistical challenges and operational costs associated with offshore deployment.

While the WSA concept offers promising synergies between renewable energy and aquaculture, several critical considerations and areas for improvement are apparent. Firstly, the feasibility and economic viability heavily rely on the ability to achieve competitive power generation and aquaculture yields. The integration of VAWTs and solar arrays on a floating platform introduces challenges such as wake effects and the dynamic stability of the structure, which could affect energy capture efficiency.

Moreover, the environmental impact assessment and mitigation strategies for such integrated systems need further exploration. Understanding the potential ecological implications of large-scale deployments, including interactions with marine ecosystems and local biodiversity, is crucial. Additionally, the WSA concept's scalability and adaptability to varying environmental conditions and regulatory frameworks require careful consideration and validation through pilot projects.

From a technological standpoint, optimizing the mooring system and addressing maintenance challenges in remote offshore locations are essential for long-term operational success. The complexity of assembling and transporting such integrated systems also necessitates advanced logistics and deployment strategies to minimize costs and risks.

Table 3. List of MUPs projects.

No.	Name of the Project	Wind	Solar	Wave	Aquaculture	Ref.	Project Status
1	The Guoneng Sharing project	✓	✓		✓	[88–90]	Operating
2	Ming Yu No. 1	✓			✓	[91–93]	Operating
3	The Blue Growth Farm (BGF) EU H2020	✓		✓	✓	[94,95]	Tested
4	AquaWind	✓			✓	[96]	Tested
5	Solar Oyster Production System (SOPS)		✓		✓	[99,100]	Testing
6	Haiwei-2		✓		✓	[101]	Operating
7	Penghu		✓	✓	✓	[102,103]	Operating
8	FP7 TROPOS Project	✓	✓		✓	[104–106]	Concept
9	Hex Box	✓			✓	[107,108]	Concept
10	The WSA Concept	✓	✓		✓	[109]	Concept

3.2. Theoretical Integrations of Offshore Wind Energy and Aquaculture

Using the foundations of wind turbines to support fish cages or nets is an inventive method. This method not only adds a substantial economic component to the marine ecology but also helps produce ecologically sustainable electricity. By exploiting the existing infrastructure of wind turbine foundations, scientists and specialists in the sector are looking at methods to promote sustainable fish farming and increase marine biodiversity.

As the monopile is one of the most often utilized offshore wind foundations, it is anticipated that a great deal of research will be conducted on this particular foundation. An example of research that makes use of this kind of basis can be found in [110]. In order to facilitate marine aquaculture, it was suggested to use a hybrid wind turbine foundation in conjunction with a double-layer offshore net cage. The addition of this double-layer design contributes to the improved diffusion of wave energy and the enhancement of the cage's stability. The foundation design has a cylindrical structure installed at the bottom and a circular friction wheel located at the mudline. This design is intended to improve the foundation's stability and create extra vertical strains in the soil.

Because the high-rise pile cap foundation is one of the most often utilized foundation types in China, this type of foundation is the subject of hybrid foundation simulations [111]. In China's waterways with depths of less than 20 m, this particular sort of foundation was used the majority of the time. This foundation integrates steel pipe piles and a concrete platform to form an enclosed space for aquaculture.

From the previous chapter, it can be noted that there is an existing offshore wind farm with a jacket-type foundation that incorporates aquaculture nets into the structure, named JOWT-SC. However, there are studies that suggest alternative solutions, such as the one mentioned in the study [112]. This study proposes a unique design for the jacket, consisting of cylindrical legs and octagonal braces that are strategically placed around the structure. These components form a cage-like structure, which is then used to secure the nets. This innovative approach to combining offshore wind energy with aquaculture suggests the use of a 10 MW turbine for the entire complex.

The Jacket-Cage system is yet another technologically advanced option that integrates jacket foundations with aquaculture [113]. When it comes to supporting fish farming activities, this design makes use of the sturdy jacket base that is typically found on offshore wind turbines. Fish are housed inside the jacket structure, which is surrounded by fishnets, to ensure their safety. This sturdy foundation is substantially heavier than traditional fish cages, which results in increased stability within the fish enclosure. There is also the possibility of incorporating auxiliary equipment inside the structure to support a variety of functions related to fish farming, such as the capability to submerge the fishnets.

In the case of integrating aquaculture nets with tripile foundations, chapter 11.4.3 from [114] analyzes different constructive models of cages specially developed for offshore wind turbines, focusing on the interaction with the tripile-type foundation. In the mentioned chapter, three different constructions of the cage are proposed: one with a cylindrical cage, the second with a spherical cage, and the third with a triangular prism cage. The size of the cage and the coupling mechanisms between the piles, along with the choices for external moorings and rigid or flexible attachments, were important factors to take into account.

When it comes to floating foundations, hybrid platforms are also used. In the research [115], a prototype known as COSPAR is studied. This prototype combines a steel cage with a floating spar structure. The model of the offshore cages used in Ocean Farm 1 and Shenlan 1 served as the basis for the design of the octagonal steel cage constructed. To ensure that the cage continues to function properly, the platform is also fitted with a wind turbine that has a capacity of one megawatt. The structure also has four catenary chains that attach to the center of the spar structure.

Semi-submersible foundations are another widely used kind for deep-sea applications that combine wind energy with aquaculture. To provide enough living space for fish and endure wave impacts, the FOWT-AC model, suggested in ref. [116], combines a 5 MW turbine with a sturdy steel frame for aquaculture. Heave plates are used to reduce heave reaction, together with four offset columns and a center column in this frame. Fish safety and buoyancy are provided by the X-shaped supports and an 18% solidity brass net system that reinforces the cage. The OC4 semi-submersible design of the mooring system guarantees safe placement in the water, while the steel frame, with its precise proportions and material qualities, guarantees the stability of the cage.

Parallel to this, a wind turbine and a hexagonal semi-submersible cage are combined in an integrated wind-energy-aquaculture structure investigated in another research [117]. Supporting offshore aquaculture operations and generating electricity from wind energy are the two functions of such a hybrid platform. Because of its buoyant hexagonal shape, the semi-submersible cage offers inherent stability in offshore situations. It may be partly submerged to meet the needs of aquaculture below and the wind turbine above. This construction improves robustness and durability since it is designed to endure intricate wave and current interactions. The foundation is surrounded by six floating ballast structures that further improve stability, which is essential for secure and effective operations. A major breakthrough in sustainable offshore engineering, the shared mooring system maximizes structural integrity and energy production efficiency.

Continuing the exploration of semi-submersible floating foundations for integrated wind and aquaculture systems, the study [118] introduces a novel approach focusing on a robust and adaptable design tailored for offshore environments. Building on prior research into semi-submersible platforms, which have been shown to be successful in supporting wind turbines and aquaculture operations concurrently, this iteration merges a 10 MW DTU wind turbine with an aquaculture cage system specifically constructed for this purpose. An underwater buoy, three slightly inclined side columns, a center column, and diagonal braces are all components of the foundation precisely developed to improve stability while simultaneously reducing fabrication difficulties and fatigue concerns. The aquaculture cage system, inspired by very successful deployments such as "Ocean Farm 1", functions as both a structural ballast and a protective enclosure. This ensures that the integrated system is both resilient and efficient.

Another recent study investigated the integration of a semi-submersible foundation for combining offshore wind energy with aquaculture, while also considering the incorporation of a point-absorber array [119]. The semi-submersible wind turbine serving as the base, modeled after the WindFloat concept, is built to resist the complex and dynamic sea environment. Its semi-submersible form consists of buoyant columns or pontoons that are partly submerged underwater. This makes it possible to achieve stability by lowering the center of gravity and limiting the motion caused by wind and waves.

An essential part of the system, the point-absorber array is made up of a few absorbers that are arranged in a strategic manner all around the floating WT. To transform mechanical motion into electrical power that can be used, these absorbers are intended to catch wave energy via the utilization of a hydraulic power-take-off (PTO) system. All the absorbers in the array are tuned for efficiency, and studies are conducted to determine the appropriate load for achieving the highest possible energy extraction. Structurally, the aquaculture cage enhances stability by acting as a damping mechanism, particularly effective in reducing heave motions induced by irregular waves. Constructed with durable materials and suspended by secure points from the platform, the cage ensures operational integrity even in challenging marine environments. All the studies used in the elaboration of this subchapter are grouped in Table 4.

Table 4. Studies involving foundations from offshore wind farms together with aquaculture.

Foundation	Name of the Study	Ref.
Monopile	Wave diffraction of a hybrid wind turbine foundation with a double-layer aquaculture cage	[110]
High-rise pile cap	Hydrodynamic analysis of a multi-pile-supported offshore wind turbine integrated with an aquaculture cage	[111]
Jacket	Dynamic analysis of an integrated offshore structure comprising a jacket-supported offshore wind turbine and aquaculture steel cage	[112]
	Jacket-Cage: Dual-use the jacket foundation of offshore wind turbine for aquaculture farming	[113]
Tripile	Aquaculture perspective of multi-use sites in the open ocean: The untapped potential for marine resources in the Anthropocene	[114]
Spar	Hydrodynamic response analysis of combined spar wind turbine and fish cage for offshore fish farms ∣ International Journal of Structural Stability and Dynamics	[115]
Semi-submersible	Modeling and dynamic response analysis of a submersible floating offshore wind turbine integrated with an aquaculture cage	[116]
	Dynamic responses of a semi-submersible integrated wind-energy-aquaculture structure under regular and irregular waves	[117]
	Numerical modeling and dynamic response analysis of an integrated semi-submersible floating wind and aquaculture system	[118]
	Experimental investigation into the dynamics and power coupling effects of floating semi-submersible wind turbine combined with point-absorber array and aquaculture cage	[119]

3.3. Numerical Simulations on the HES

The WSA concept project, which combines solar, wind energy, and aquaculture as presented in the Section 3.1, was also the subject of hydrostatic, hydrodynamic, and stochastic analyses [109]. The analyses were conducted using several software programs. The ABAQUS v14.0 program was used to analyze the hydrodynamic reaction of the structure under calm water conditions. WAMIT v7.0 software was used for frequency analysis using the potential flow theory. MultiSurf v8.5 software was used to generate the constructive structure of the concept. The free decay test analysis used the OrcaFlex program. The system demonstrates exceptional motion characteristics compared to conventional offshore wind concepts like OC3Hywind and OC4DeepCwind. Thanks to its larger displacement and dimensions, it naturally offers greater stability and is less influenced by wave frequencies. However, accurately capturing damping effects, especially from fish nets and slender members, continues to be a challenge. These factors have a significant impact on the dynamic response and necessitate further refinement in numerical modeling. In addition, when examining complex environmental factors such as wind, waves, and current, the study of stochastic processes reveals that the WSA demonstrates resilience and minimal structural dynamic non-linearity. This suggests it could be a practical choice for the offshore energy sector. Future work should concentrate on improving damping models, analyzing the system reaction to different environmental loads, and optimizing mooring to achieve maximum effectiveness. Enhancing deployment capabilities and guaranteeing reliable performance in various offshore circumstances depend heavily on these developments.

The examination of the JOWT-SC concept [112] is a significant contribution to this area of study. This study used SACS software for time-domain simulations to analyze the dynamic responses of the integrated structure under different environmental conditions. The research emphasizes the significant impact of the steel cage used in aquaculture on the total dynamic responses of the integrated structure. One crucial piece of information is that the cage reduces pile-foundation shear at the mudline by up to thirty percent when subjected to wind loads alone. This is in contrast to a comparable OWT structure that lacks a cage. Conversely, the shear force on the pile foundation at the mudline can increase by up to fifty-five percent when the effects of wind, waves, and currents are taken into account. The reason for this is the increasing hydrodynamic pressures exerted on the cage. Furthermore, the study demonstrates that the JOWT-SC has heightened sensitivity to wave frequencies beyond its first two natural frequencies. This highlights the need for meticulous examination of wave phenomena throughout the whole design phase. While the study yielded valuable insights, it also identified inconsistencies in the dynamic responses under high-stress scenarios. This suggests that there is a need for further improvement of numerical models and verification via comparison with experimental data. These results add to a more in-depth knowledge of the interactions between offshore wind turbines and aquaculture facilities, opening the way for hybrid energy systems that are both more efficient and more durable. Further investigation is necessary to resolve the observed inconsistencies and enhance the design and performance of integrated systems.

A comprehensive numerical study was conducted on a high-rise pile cap construction to get a thorough understanding of the net cage effect [111]. The primary objective was to comprehend the dynamic impact of the cage. The results indicate that the wind turbine's structural frequency is not significantly impacted by the net cage. However, there is a notable rise in hydrodynamic forces exerted on the foundation. More precisely, the computational fluid dynamics (CFD) simulations showed that the net cage produces significant alterations in the flow field around the foundation, leading in increased hydrodynamic loads. These loads were discovered to be highly concentrated in the upstream area of the structure, with one pile experiencing a load increase of up to 6.32 times its initial value. The heightened load presents substantial hazards to the structural stability of the wind turbine base, emphasizing the need for meticulous deliberation throughout the design phase.

The development of sophisticated numerical models using linear potential theory and eigenfunction expansion methods to accurately simulate hydrodynamic loads and wave interactions was investigated in [110]. The exploration of diverse configurations and parameters, such as porosity, net spacing, and friction, has been highlighted as strengths. This research suggests positive future directions. Researchers must continue to study net material durability and biofouling mitigation measures, which could affect structural integrity and operational efficiency. Further research should refine model predictions under dynamic and extreme environmental conditions. These integrated systems' economic viability and scalability must also be assessed for wider adoption. Validating theoretical models and optimizing design parameters for real-world applications will require robust field testing and monitoring systems.

The purpose of the study [115] is to investigate the hydrodynamic response of the COSPAR fish cage, which is a one-of-a-kind offshore hybrid platform that blends a semi-submersible fish cage architecture with a floating spar wind turbine. Through the use of numerical analysis in ANSYS AQWA, it explores the stability of the platform in terms of heave and pitch motions, as well as its resistance to viscous damping and mooring line tensions under a variety of wave conditions. In contrast to other hybrid platforms, COSPAR emphasizes its semi-submersible nature by using offshore wind turbines for power production. This enhances the platform's ability to support dependable aquaculture operations in harsh marine circumstances. The study successfully exhibits COSPAR's better hydrodynamic performance by demonstrating higher stability in heave and pitch motions. This is in contrast to standard semi-submersible cages that are less stable. This highlights the relevance of these findings for early design reviews and demonstrates that linearized drag assumptions may be successfully applied to frequency domain research. Furthermore, the investigation of wave attenuation via the use of a porous wave fence located above the cage provides significant new insights into the techniques that may be used to maximize the well-being of fish and minimize their impact on the environment.

Currently, the focus of emphasis for future research is on refining the design specifications and operation procedures of COSPAR. This is being conducted to ensure that offshore aquaculture is both scalable and economically viable. Furthermore, to assess nonlinear influences and long-term structural integrity in realistic operating conditions, it is important to conduct comprehensive validation utilizing advanced time domain models. It is necessary for future study to explore the combined aerodynamic and hydrodynamic interactions between the fish cage and the wind turbine. This is necessary to enhance the structural stability and energy production in a way that is complimentary.

A second study examined wind and wave coupling effects on the integrated offshore platform after the first study examined the hydrodynamic response of the COSPAR fish cage [120]. This second study uses ANSYS AQWA to simulate COSPAR's motion responses under combined wind and wave stresses in the frequency domain (FD). A linearization approach based on predetermined thrust coefficients was used to predict wind thrust for surge, pitch, heave, and mooring tension movements to yield reaction amplitude operators (RAOs). Based on the initial study's results on COSPAR's stability and hydrodynamic performance, this study examined wind-induced effects. The research focused on wind-wave coupling rather than wave attenuation and heave and pitch stability, confirming the FD technique by comparing it to the DeepCwind floating wind turbine model. COSPAR had steadier and less noticeable RAOs in surge, heave, pitch, and mooring tension than DeepCwind, indicating a strong coupling effect in pitch motion.

The FD analysis conducted in this work demonstrated the stability of COSPAR under the combined influence of environmental factors, thereby validating its suitability for offshore fish farming. The study demonstrated that the porous collar barrier and semi-submersible architecture developed by COSPAR effectively reduce wave transmission and dissipate energy, resulting in enhanced hydrodynamic stability. The reduced FD technique accurately forecasted the interconnected motion responses caused by both wind and waves, which is valuable for conducting preliminary design assessments.

The FOWT-AC, a floating offshore wind turbine connected with a steel aquaculture cage, is a revolutionary idea presented in reference [116]. The research uses a fully coupled aero-hydro-elastic-servo-mooring model created with FAST v6.0 and ANSYS AQWA 2019 R1 software, and uses the NREL 5-MW offshore baseline wind turbine. The study looks at the integrated system's dynamic properties and performance under different ocean conditions. It finds that the pitch-torque control system effectively regulates the system's power output. Combining floating wind turbines with aquaculture cages maximizes the benefits of ocean resources, reduces the cost of long-distance transmission, and promotes environmental sustainability. Deep-sea applications do not lend themselves to traditional fixed foundations, which is why floating foundations such as spar types, TLPs, and semi-submersibles are being investigated. This work explores the hydrodynamic behavior of the combined FOWT-AC system and the aquaculture cage using frequency- and time-domain simulations, showing notable dampening effects and controllable dynamic responses. Results show that the integrated system performs well in a variety of wind and wave situations, potentially providing increased stability and economic advantages.

Even though the study reveals encouraging findings, further investigation is required to fully realize the FOWT-AC system's potential. To support the numerical modeling and validate the system's operation in real-world conditions, experimental validation is crucial. Optimizing the structural design will also guarantee long-term strength and durability, particularly in the event of severe weather. It will be essential to look at how the floating wind turbine and aquaculture cage interact, especially with respect to how it may affect marine life and the environment. Investigating cutting-edge control techniques may also save maintenance costs and extend the integrated system's fatigue life. All things considered, the study offers a solid basis for the FOWT-AC idea, and further research in these fields will be necessary to see it through to effective implementation.

3.4. Basin Measurements on the HES

Another method to analyze the dynamic characteristics of the structure is through experimental measurements. Such measurements were carried out on the Blue Growth Farm (BGF) project at Ecole Centrale de Nantes, France [121]. The main goal of the study was to understand the platform's behavior and validate numerical models dynamics under different configurations. To achieve this, a 1:40 scale model was carefully studied.

In the experimental set-up, extensive testing was carried out in Hydrodynamic and Ocean Engineering Tank (HOET). The tank provided a controlled way for basin measurements of pitch, heave, and surge motions, without considering wind effects. Three distinct configurations were analyzed—with and without WECs, and with the cage—to see how fish cages and WECs affected platform dynamics. These setups made it possible to gather data via in-depth measurements and video recordings, which are essential for verifying numerical models and improving platform design.

Significant asymmetries in motion and moonpool water elevation were found during the wave-frequency response experiment, especially during key wave intervals. This feature, in conjunction with the study of drift behavior and the impact of WEC calibration on motion dynamics, highlighted how comprehensively the study examined the platform's performance in simulated environmental settings.

As a result, even though this experimental study offers crucial information and understandings into the dynamic behavior of the BGF platform, it also points up several issues that need further research. More research is required to fully understand the complicated coupling effects between the technologies and platform movements, nonlinear events, and the influence of WEC calibration. To provide a thorough and trustworthy description of the platform dynamics, the results highlight the need for creating and verifying coupled numerical models. Future studies should consider coupled wind-wave solicitations, irregular sea states, and inclined wave conditions to further understand and optimize the platform's performance in practical settings.

Another study that involved basin measurements was conducted at Shanghai Jiao Tong University's Ocean Engineering Basin [122]. The purpose of the study was to investigate the dynamic response in different environmental conditions of the semi-submersible type structure with an aquaculture cage. Both the effects of water and wind were simulated for the study, using advanced tools. A 1:40 scale model was used for the study, with three cable mooring lines incorporated, and the test depth was 0.875 m.

The study involves several aspects, such as calm water, white noise wave, irregular waves, wind, and waves. For the wind simulation, a 3×3 array axial fan system was used to generate constant air, and a honeycomb fairing was employed to improve the wind field quality and uniformity.

The study presents important information regarding the dynamic response of the structure and represents a solid foundation for research, and in the future, it could be used to simulate more diverse extreme conditions not addressed in this study. An important aspect identified is that the nets increase the damping effect and influence the natural frequencies of the motions, this aspect being able to serve as a foundation for future studies that analyze different configurations of the net as well as the materials of which it is made. Although the calibration of the environmental conditions was carried out with precision, future validations with the scale model would further strengthen the findings, to accurately describe the dynamic behavior of the structure.

According to the study [123], integrating a cylindrical fish cage with a tripile base could meet the growing demand for fish and algae products as global fisheries production stagnates. The study examines aquaculture fish cage–tripile foundation interactions using a 1:40 scale physical model. It explores wave-induced particle velocity variations, force distribution, and fish cage scour.

Wave-induced particle velocity and distribution around the support structure with the fish cage were tested in the model. The research also considered fish cage stresses on the tripile and foundation scour. Physical model tests are crucial as they reveal cage–foundation interactions that numerical research cannot simulate. Study findings include fish cage-induced velocity regime alterations near the OWEC (Offshore Wind Energy Converter) structure. Such adjustments are necessary to comprehend how wave forces cause mechanical stress on the structure. Particle Image Velocimetry (PIV) and Acoustic Doppler Velocimetry (ADV) provided precise measurements of 3D velocities and revealed the fish cage net material's dampening effects.

Force experiments showed non-linear connections between wave heights and response forces, with additional net layers dramatically increasing the forces. Aquaculture efficiency and structural integrity must be balanced in net design. With optical tools, the study examined scour evolution around the tripile legs and estimated local seabed alterations. These measures are essential for structure stability. Fish cages in tripile foundations can be integrated with controlled stresses and velocity variations, according to the study. We need more research to improve the design and understand long-term effects, especially under different environmental conditions. Optimization of the net material and configuration, and longer-term research on the hybrid system's endurance and economic viability should be the next steps.

However, more study is necessary to improve the design and provide a thorough knowledge of the long-term impacts, especially considering changing climatic circumstances. Future study should focus on optimizing the net material and design, as well as conducting long-term studies to assess the economic feasibility and longevity of such hybrid systems. Similar to previous studies, the findings support the idea of integrating aquaculture and offshore wind energy on a one-to-one basis.

In a similar vein to the preceding study on semi-submersible platforms, the following research investigates the dynamic responses of a wind-energy-aquaculture integrated structure using basin measurements [117]. The experimental setup at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China, used sophisticated measuring and analytical methods. Data processing and analysis were conducted using advanced software tools, while motion responses were tracked using optical methods. The study employs a scaled physical model at a ratio of 1:100 to simulate real-world conditions for offshore aquaculture and renewable energy integration. The experimental setup features a hexagonal semi-submersible cage as the foundational base for a 5 MW wind turbine, aiming to explore the feasibility and performance of MUPs in marine environments. To obtain accurate findings regarding the structural behavior and dynamics of the mooring system, as well as to assure a near resemblance to the full-scale prototype, careful consideration was given to the selection of dimensions and material characteristics.

The scaled model was tested in a controlled wave environment, experiencing diverse wave conditions, such as regular and irregular waves of varying heights and durations. Precise measurements of the wave characteristics were acquired using a digital wave gauge with a measuring range of 0–600 mm and minimal measurement error. Sophisticated data gathering methods were used to record and evaluate the pitch, heave, and surge motions of the integrated system.

To simulate real-world mooring conditions, two configurations were assessed: tight mooring and catenary mooring systems. The mooring lines were meticulously designed to preserve the elastic and geometric properties of the full-scale prototype. The mooring line tensions were monitored using waterproof tension sensors (KD41100), which provided accurate measurement and control with a 0.5% error tolerance.

While the study presents comprehensive data on the stability and efficacy of integrated wind-energy-aquaculture structures under varying wave situations, there are unanswered concerns. Areas that may need more investigation include the enduring resilience to severe weather conditions, the verification of outcomes on a larger scale via scaling effects, the enhancement of numerical models for wider applicability, and the optimization of integrated offshore platforms.

The study referenced in [118] stands out for its comprehensive integration of numerical models and basin measurements in the analysis of MUPs. This unique approach combines the predictive power of numerical simulations with empirical data from basin measurements to provide a thorough assessment of platform dynamics, environmental impact, and operational feasibility in marine environments. The purpose of this research is to investigate the dynamic responses of an integrated system consisting of a semi-submersible floating wind turbine and an aquaculture cage. The goal of the study is to maximize the use of offshore areas to produce renewable energy and support sustainable aquaculture activities.

SIMA software is used for the purpose of conducting numerical simulations in this work. These simulations include extensive modeling of hydrodynamic, structural dynamic, and aerodynamic processes. For the purpose of achieving a realistic simulation of the hydrodynamic interactions between the aquaculture cage and the floating platform, the screen technique is used to represent the hydrodynamic load placed on the aquaculture cage. This approach divides the forces exerted on the net panel into two components: drag and lift.

In the Deepwater Offshore Basin at Shanghai Jiao Tong University, the numerical model is verified using wave basin model tests conducted at a scale of 1:64. To guarantee the dependability of the results, the tests verify that the simulations are accurate. These simulations encompass natural frequency, damping coefficients, and response amplitude operators (RAOs) for each platform motion.

In the presence of coupled wind, wave, and current conditions, the incorporation of aquaculture cages results in a considerable reduction in pitch motion by 7.69%, while simultaneously causing an increase in mean surge response of up to 12.6%. To preserve the structural integrity, the mean mooring loads should not increase by more than 15%. There is only a 2% variance under circumstances of rated wind speed, indicating that the system can stabilize offshore wind turbines without substantially impacting power production. The integration also has a limited influence on the efficiency of power generation.

In addition to highlighting the significance of considering combined wind, wave, and current conditions in dynamic response analysis, this study also proposes that other environmental situations, such as various wave and current orientations and severe sea conditions, should be the subject of future investigation. Detailed strength and fatigue evaluations are required to conduct a comprehensive evaluation of the system's viability and to optimize its design requirements. There is considerable potential for sustainable offshore development and effective use of wind energy, as shown by the results, providing vital insights into the combined use of offshore wind and aquaculture systems.

4. Environmental Aspects

The incorporation of MUPs for offshore projects involves intricate interactions between environmental advantages and difficulties. These platforms, which integrate features like offshore wind, wave energy, and aquaculture, are specifically built to maximize the efficient use of space and resources. Nevertheless, they give rise to substantial environmental consequences that need thorough evaluation and control.

The environmental consequences of MUPs vary depending on their design, location, and operating methods. Fixed installations need substantial disturbance of the seabed, whereas floating systems such as WaveStar have difficulties pertaining to anchoring and stability [124]. The choice of foundation, which may vary from fixed to mooring systems, impacts benthic organisms and the integrity of the bottom [125]. Moreover, the materials used in these platforms can attract new organisms, while the process of biofouling might make maintenance more challenging and lead to increased friction [125].

The issue of noise and vibration caused by wind turbines and wave energy converters (WECs) is of great importance. The effects of these consequences on marine species, such as birds and mammals, have the potential to cause alterations in their behavior and habitat use. The visual effect, particularly of wind turbines, is another significant influence, especially when these structures are seen from the shoreline [125].

Integrating aquaculture into MUPs introduces other environmental factors to be taken into account. The main issues are nutrient contamination and habitat modification, especially in fish farms, which emit a greater amount of organic matter compared to shellfish farms [126]. The incorporation of antifouling agents and other chemicals exacerbates the environmental impact of these systems [124].

Various case studies illustrate the varied environmental effects of MUPs in various areas. The TROPOS project highlights the significance of integrating environmental factors at the first stage of the design process. Environmental impact assessments (EIAs) were used to detect and address possible hazards, such as noise pollution, artificial lighting, and waste disposal, in projects such as the Green & Blue platform in Crete and the Leisure Island in Gran Canaria. The study discovered that MUPs often had less negative environmental impacts compared to single-use platforms. This highlights the need of thorough planning and cooperation [106,127].

The Jacket-Cage system [113], for example, effectively reduces fish escape events and eliminates pollution caused by aquaculture operations, thanks to its sturdy and secure construction. Operating in high-energy offshore areas improves water quality for fish farming, which has the potential to result in higher-quality products. The incorporation of aquaculture into offshore wind farms boosts their financial sustainability by adding an extra source of money, while also offering a sustainable and ecologically good option.

The environmental implications of MUPs are greatly influenced by their deployment places. Unique marine environments provide distinct challenges and opportunities, necessitating tailored approaches to mitigate adverse effects. For instance, the study carried out by [10] shows that the Atlantic and Baltic areas have distinct natural features, resulting in a wide range of technical and environmental difficulties. The Atlantic site, known for its more severe maritime conditions, presents more technical challenges and environmental hazards as compared to the Baltic location. The variances underscore the need of undertaking site-specific environmental assessments and applying customized mitigation measures to meet the unique impacts of each location.

The integration of floating offshore wind (FOW) platforms with aquaculture, especially in areas such as the Gulf of Lion, offers both ecological advantages and hazards. This strategy may mitigate the impact of nutrient release on coastal areas, therefore safeguarding beach tourism districts [128]. Nevertheless, the ecological consequences of aquaculture, such as the discharge of organic debris from fish farms, need meticulous oversight [126].

The EIA framework, as outlined in recent EU directives, is crucial for evaluating the potential effects of MUPs on marine ecosystems [127]. This comprehensive process includes screening, scoping, alternative examination, impact analysis, and mitigation planning. Key environmental concerns addressed in this framework include disturbance to marine biota, risks to native species and habitats, visual and noise pollution, and potential alterations to coastal dynamics. The valuation of ecosystem services using the Total Economic Value (TEV) approach provides a thorough assessment of both the economic costs and benefits associated with environmental changes caused by MUP operations [129].

5. Economical Aspects

The potential for innovation and cost-effectiveness is evident when examining the economic environment of MUPs that combine aquaculture and renewable energy. According to studies like those referenced in [130–132], the economic feasibility of MUPs hinges on various factors, including cost-effectiveness, operational efficiencies, and the potential for revenue diversification. For instance, standalone MUPs are favored over grid-connected solutions due to their potential for greater innovation and lower environmental impact [124].

The economic advantages of MUPs in industries such as energy, aquaculture, transportation, and leisure are shown by the TROPOS project [106]. To improve commercial viability, the study highlights the significance of integrated deployment tactics. Economic effect analyses show that there are considerable regional gains in Gross Domestic Product (GDP) and employment, demonstrating how MUPs may boost local economies. The wind–mussel combination [132] demonstrates how economic viability evaluations, bolstered by competitive levelized costs of power and mussel production, show positive investment return rates (IRR) of 10.8%. To enhance long-term sustainability and commercialization, policy options include infrastructural development and tax incentives. This integrated system not only ensures competitive Levelized Cost of Energy (LCOE) but also supports marine ecosystem health and food security, highlighting its appeal as a sustainable commercial model.

Furthermore, some case studies, such as the Jacket-Cage concept [113], showcase creative ways to use offshore wind turbine foundations for aquaculture and energy extraction, saving a lot of money by doing away with the need for extra mooring systems and seabed footprint. By combining aquaculture with offshore wind, the proposal described in [87] shows a 44% increase in yearly yields, emphasizing significant income potential despite modest increases in LCOE because of aerodynamic performance issues. Economic modeling shows that adding fish farming to offshore wind farms may boost profits considerably without adding a considerable amount of new expenditures, thereby encouraging effective use of ocean space.

Regarding technological integration and financial constraints, studies such as the one presented in [119] on wave-wind-aquaculture hybrid systems offer a thorough investigation of Levelized Cost of Energy (LCOE). Evaluating economic viability depends on this indicator, which shows how aquaculture and WECs can lower LCOE by 1.5% by means of increased power output and operational synergies. Optimizing power take-off systems and fully utilizing aquaculture's economic contributions still present difficulties, though.

Another example of a successful outcome is the research on offshore mussel production within wind farms [133], which shows that a 1000-hectare mussel farm with potential revenues of €39 million and a net profit of €9 million can produce profitable results. Sensitivity analysis highlights the economic resilience of integrated aquaculture–wind energy systems by emphasizing the significance of stable market conditions and successful cost management techniques in sustaining profitability.

As [134] discusses, policy frameworks are essential for enabling multi-use arrangements through programs such as maritime spatial planning (MSP). MSPs can support sustainable economic growth in industries like aquaculture and renewable energy while optimizing marine space efficiency by promoting co-location strategies and lowering regulatory barriers.

6. Legal Framework

We may state that the legal framework that pertains to MUPs is rather vague. This is something that we can claim. Due to the fact that each activity is subject to its own regime and rules, there is currently no legal framework applicable to all the fields mentioned in the work [135]. As a result, the process of obtaining approvals and other operating documents will be directed to various competent authorities. This will result in a more laborious process, leading to higher installation costs, as well as the appearance of barriers related to the development of these fields [10,136]. As a consequence of this, the legal framework to which this sector is subject is increasingly fragmented and confusing. On the other hand, a number of laws have been passed covering various areas of aquaculture and the management of renewable resources. As an illustration, the European Union (EU) has enacted the Marine Spatial Planning Directive (MSP Directive) 2014/89/EU [137], which mandates that all activities in the spatial plan, including aquaculture and renewable energy, be taken into consideration. This directive is part of the Integrated Maritime Policy (IMP) for the European Union [138]. There is also a legislation in the United States that is somewhat similar to this one, and it is called the Coastal Zone Management Act (CZMA) 1972 [139].

The challenges discussed earlier may be resolved by including a class law directed at these MUPs, which can make it easier for the many branches that are a part of it to work together.

7. Conclusions

There has been a surge in interest lately in investigating novel platforms that combine aquaculture methods with renewable energy sources. Several innovative projects that demonstrate this tendency have been discussed in this study. They include sophisticated aquaculture systems connected with offshore wind farms, wave farms, and solar farms. Despite these encouraging advancements, there is still a dearth of research on MUPs, which may be attributed to the technology's infancy and the preponderance of single-purpose, single-discipline studies.

The current literature emphasizes an increasing amount of research concentrating on MUPs, particularly those combining offshore wind technology with aquaculture facilities. However, detailed studies that combine numerical analysis with basin measurements to evaluate these integrated systems are still limited. Advanced numerical models, such as computational fluid dynamics (CFD), combined with empirical data from basin measurements, are critical for anticipating environmental consequences, optimizing resource consumption, and assuring operational feasibility. Basin measurements also provide empirical data on local maritime conditions, which helps to validate model results and influence real-world implementation tactics.

Overall, the economic outlook for MUPs is very promising, as they provide a unique opportunity to combine renewable energy and aquaculture in a way that not only leads to substantial cost savings and income generation, but also promotes sustainable development. The economic viability of MUPs depends on maximizing resource use and operational efficiency. To fully unlock the economic benefits of marine protected areas, it is essential to make use of favorable regulations and cutting-edge technology. This will contribute to the development of a strong and successful marine economy.

Finally, it should be noted that integrating MUPs into offshore projects presents the twin problem of maximizing financial gains while minimizing environmental damages. By integrating offshore wind, wave energy, and aquaculture, these platforms provide opportunities for resource and space efficiency. Seabed disruption, noise pollution that harms marine life, and aquaculture-related nutrient contamination are some of the concerns they also present. EIAs that are thorough and customized mitigation plans for each site are necessary to address these problems. To effectively use MUPs' potential for both ecological preservation and economic growth in the future, it is necessary to retain a commitment to environmental standards while innovating in technological integration.

All while embedding circular economy concepts to unlock and sustain the transforming potential of multi-use platforms, future research must critically advance computational models integrated with empirical data, enforce rigorous, site-specific environmental assessments, innovate hybrid renewable energy systems, conduct granular economic viability studies, and prioritize long-term ecological impacts and climate resilience.

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