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Offshore multi-purpose platforms for a Blue Growth: a technological, environmental and socio-economic review

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Abstract

"Blue Growth" and "Blue Economy" is defined by the World Bank as: *"the sustainable use of ocean resources for economic growth, improved livelihoods and jobs, while preserving the health of ocean ecosystem"*. Multi-purpose platforms (MPPs) can be defined as offshore platforms serving the needs of multiple offshore industries (energy and aquaculture), aim at exploiting the synergies and managing the tensions arising when closely co-locating systems from these industries.

Despite a number of previous projects aimed at assessing, from a multidisciplinary point of view, the feasibility of multipurpose platforms, it is here shown that the state-of-the-art has focused mainly on single-purpose devices, and adopting a single discipline (either economic, or social, or technological, or environmental) approaches. Therefore, the aim of the present study is to provide a multidisciplinary state of the art review on, whenever possible, multi-purpose platforms, complementing it with single-purpose and/or single discipline litera-

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ture reviews when not possible. Synoptic tables are provided, giving an overview of the multi-purpose platform concepts investigated, the numerical approaches adopted, and a comprehensive snapshot classifying the references discussed by industry (offshore renewables, aquaculture, both) and by aspect (technological, environmental, socio-economic). The majority of the multi-purpose platform concepts proposed are integrating only multiple offshore renewable energy devices (e.g. hybrid wind-wave), with only few integrating also aquaculture systems. MPPs have significant potential in economizing CAPEX and operational costs for the offshore energy and aquaculture industry by means of concerted spatial planning and sharing of infrastructure.

Highlights

- A number of projects on multipurpose platforms, aiming to conduct multidisciplinary feasibility assessments, have been done.
- Despite them, there is a lack of multidisciplinary analyses for multipurpose platforms.
- This work therefore aims at reviewing state-of-the-art multidisciplinary analyses on MPPs, complementing them with the review of single-purpose, single discipline analyses when necessary.
- A review of technological, environmental, and socio-economic analyses of ORE devices and aquaculture systems is given.

Keywords: Multi purpose platform, multi use platform, marine renewable energy, offshore wind, wave, aquaculture, social science
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1. Introduction

1.1. Context

The marine environment represents a vast source of renewable energy. Energy is available in multiple forms - wind, wave, tides, currents, and temperature and pressure gradients. The successful commercial exploitation of these energy sources is perceived as a key target to be able to tackle the energy trilemma [1]: to provide secure, sustainable, and affordable energy. However, targeted installed capacities for 2050 (460 GW for offshore wind [2] and 188 GW for tidal and wave [3]) can be achieved only by lowering the cost of the energy produced, possibly through the combined extraction of more than one marine resource. In this regard, offshore wind farms and aquaculture have been proposed as suitable candidates for co-location/multiple use, in the recent past [4, 5, 6].

Of the various offshore renewable energy (ORE) systems, bottom fixed offshore wind turbines can be considered as commercially mature. On the other hand, floating offshore wind turbines (FOWTs) have been slowly evolving from concepts to reality [7], in recent decades. This upswing in the demand for FOWTs has been brought about by a combination of several factors - stronger and less turbulent offshore winds, reduced visual pollution and mulit-use conflicts, for instance. However, other offshore renewable energy (ORE) systems, such as wave energy converters, still need to be further developed, in order to be considered commercially competitive.

In parallel with the energy trilemma, the Food and Agriculture Organization (FAO) estimates that, by 2030, the demand for seafood will exceed the supply by 40 million metric tonnes [8]. With constraints limiting the possibilities for the expansion of inland and near-shore fisheries, offshore aquaculture has emerged as a viable alternative for increasing the global seafood production. Aquaculture is classified as offshore, if it takes place in the open sea, exposed to significant met-ocean conditions [9]. Notwithstanding the challenges posed by the open ocean, offshore farming offers several advantages - increased possibilities for expansion, reduced exposure to pollution from human sources and the potential of co-locating infrastructure with ORE systems to reduce competition for operational space [10].

Thus, a proposed solution for a reliable energy extraction and aquaculture development, while addressing the questions of CAPEX, space limitation and operational safety could be the use of Multi-Purpose Platforms (MPPs). Ideally, an MPP is an offshore structure able to exploit the synergies between ORE systems and aquaculture systems, avoiding by design the conflicts arising from the close co-location of these systems. MPPs are expected to bring about significant cost reduction, by allowing multiple use of space and infrastructure, through co-located and shared technologies [11, 12]. MPPs would also promote an optimization of the marine spatial planning, proposing an efficient, integrated, sustainable, and ecological use of oceanic resources through shared spaces and infrastructure [12, 13, 14].

Furthermore, for remote and island communities, not able to access the utilities grids, an MPP may constitute the only secure, sustainable, and affordable source of energy [15, 16], food, and jobs.

1.2. Aim, objectives, and structure of the review

Despite a number of EU-funded projects aimed at assessing the feasibility of multipurpose platforms, also highlighting the importance of a multidisciplinary approach, it is here shown that the analyses available in the literature are (expect for very few cases) mainly focused on single-purpose devices, or at best hybrid wind-wave offshore renewable energy devices, and tackling the challenge only from a single discipline (either technological and/or economic, or social and/or economic, or environmental) point of view.

Therefore, the aim of the present study is to provide a state of the art review on, multidisciplinary technological, economic, and socio-environmental reviews on offshore multi-purpose platforms. This is to provide the ideal basement for a truly multi-purpose, multi-discipline analysis framework, for current and future projects looking at MPP systems. The scope of this review is limited to the most developed ORE resources - wind and wave.

While the terms MPP and multi-use of ocean space (MUS) are often used interchangeably, the distinction between the two has to be clearly understood. While MPP refers to a structure capable of exploiting the synergies between different ORE systems or aquaculture, MUS has a more general definition - ‘the joint use of resources in close geographic proximity by either a single user or multiple users’ [17] *i.e.*, not necessarily a single platform.

1.3. Overview of previous projects

Combining different ORE systems onto the same platform structure offers several benefits: increased, more consistent power production, thanks to the different patterns of different renewable energy sources, lower CAPEX-to-rated power ratio, shared balance-of-plant operations and maintenance (O&M) costs, positive dynamics interactions (e.g. wave energy converters (WECs) as additional damping systems for the OWT with which are coupled, ensuring a lower response to waves), are some of the main technological advantages. Pérez-Collazo *et al.* [18] have also identified potential project and legislative synergies. During the past decade, several European projects have investigated the technical challenges of combined ORE extraction systems. The design concepts defined by these projects are explained in detail, in the following paragraphs.

The MARINA platform project [19] identified three designs of OWT-WEC combinations for further study - the spar torus combination (STC), the semi-submersible flap combination (SFC), and the ‘OWC’ array with a wind turbine. In the STC [19], the NREL 5-MW OWT [20] is supported on a spar, and the torus (an axisymmetric point absorber that operates mainly in heave) extracts wave energy by moving along the spar, by means of a hydraulic power take-off (PTO) system. The SFC [21] comprises a semi-submersible floater with four columns (one at the centre and three at the sides) connected by means of pontoons. The central column supports the turbine and rotating flaps hinged at the pontoons capture the wave energy, making use of a hydraulic PTO system to generate electricity. The OWC array consists of a large floater having multiple WECs and supporting a single wind turbine [22].

The ORECCA project [23] classified combined platforms into offshore hybrids and energy islands. The former refers to a combination of wind and wave (or tide) energy devices, while the latter denotes large multi-purpose platforms capable of utilizing multiple sources of ocean energy, possibly in combination with an offshore harbour [24].

A modular approach for multi-purpose platforms, combining the attributes of transport, energy, aquaculture and leisure (TEAL) was proposed by the TROPOS project [25]. Different TEAL modules can be accommodated around a central unit to cater to the local socio-economic and environmental conditions, thus affording flexibility to the concept.

The H2OCEAN [26] project proposed multi-purpose platforms aimed at the production of hydrogen, perceived as the future energy vector. A farm of hybrid floating wind-wave energy devices, coupling a 5MW H-type vertical axis wind turbine (VAWT) with a WEC, provides electricity to a central platform, where the energy is transformed into hydrogen, and to an aquaculture system.

The MERMAID project [27] explored the possibility of using innovative multi-purpose platforms for combining food (aquaculture) and energy production, on the basis of site-specific environmental challenges.

The W2Power concept supports two WT's on a triangular platform, with WEC's attached in arrays along the 3 sides [28]. Each platform has been envisaged to reach a rated power around 10 MW. The WindWaveFloat intends to equip the WindFloat (a semi-submersible type FOWT structure with three columns) with different types of WECS, such as OWC's and point absorbers [29]. The addition of the WEC's were observed to have minimal influence on the motion of the support structure.

The Poseidon, developed by Floating Power Plant A/S, is a semi-submersible platform for combined wind-wave energy extraction, which can support 10 floating wave energy absorbers (3 kW) and 3 wind turbines (11 kW) [30]. The Wave Dragon, a multi-MW overtopping WEC, has been a pioneer in the field of wave energy generation [31]. The Wave Dragon is also capable of supporting two 2.3 MW wind turbines, with significant savings in the levelized cost of energy

(LCoE) [32].

1.3.1. *MPP: comparison of functionality*

The functionality of the MPP concepts discussed above are compared in Table 1. It is noticeable how the majority of the platforms are hybrid wind-wave energy devices, with only a few including aquaculture systems. Furthermore, it may be noted that majority of the concepts are publicly funded and subsidized, thus highlighting the novelty of the platforms. Also, the rated power varies from 10^2 to 10^4 W, reflecting the potential variety of applications and markets of the MPP concepts.

Table 1: MPP concepts - Comparison of functionality

No.	Platform	Wind	Wave	Aquaculture	Solar
1	Sea Star Spar [33]	✓		✓	
2	STC [19]	✓	✓		
3	W2Power [28]	✓	✓		
4	SFC [21]	✓	✓		
5	OWC Array [22]	✓	✓		
6	Poseidon [30]	✓	✓		
7	TROPOS [34]	✓		✓	✓
8	MERMAID [35]	✓	✓		
9	WT - feed barge[36]	✓		✓	✓
10	Ocean Farm1 [37]			✓	
11	Wave Dragon [31]	✓	✓		

Over 200 scientific articles have been accessed as part of the present review paper, with most of them ($\sim 70\%$) published during or after 2010. The methodology to organise this multidisciplinary review has been the following the selected papers were initially classified on the basis of the discipline they represent - technological (section 2), environmental (section 3) and socioeconomic (section 4). Further, the literature reviewed in each section has been subdivided with respect to the resource they exploit - ORE (wind, wave or combined) or aquaculture. As overarching topic, including aspects from different disciplines, the studies related to MPPs and risk are reviewed in section 5. An overview and discussion of the literature reviewed is presented in section 6, with conclusions provided in section 7.

2. Technological aspects

2.1. ORE

The following subsections discuss the technological aspects of combined ORE systems, where the outcomes of the previous projects have been highlighted. While most concepts from these projects have been subjected to numerical modelling studies, a few of them have reached the stage of experimental testing as well. The approaches followed in numerical modelling and experimental testing have been mentioned in detail. Aquaculture systems (both standalone and integrated with ORE devices) have also been discussed. A review of the control aspects of MPPs is also presented in this section.

2.1.1. Model of dynamics: numerical and experimental methods

Several MPP systems described in Section 2.1 have been subjected to numerical modelling. The SFC and the STC have been numerically analyzed in the time domain [38, 39], by coupling the SIMO [40] and RIFLEX [41] software. SIMO is used to compute the hydrodynamic loads on rigid floating bodies. RIFLEX is a nonlinear program for modelling wave loads on slender structures, like mooring lines using the Morison equation, and aerodynamic loads on wind turbine blades using blade element momentum (BEM) theory. The models were a combination of flexible and rigid bodies, and potential theory was used to estimate the wave loads. The same approach was adopted to model the WindWEC [42], a hybrid combination of the Hywind SPAR [43] and the Wavestar [44] WEC buoy.

Soulard *et al.* [45] used a wave to wire representation based on linear potential theory to model the fluid-structure interaction of a 100 m diameter circular hybrid platform (C-HyP), supporting the NREL 5-MW OWT, and an array of oscillating WECs. Aerodynamic loads were imposed at the nacelle, through a simplified procedure [46] which makes use of the relative wind speed with respect to the platform motion. The motion of a multi-use platform (MUP) developed for the MERMAID project [47] was studied in the time domain, using the open source boundary element method solver, NEMOH [48]. A coupled system of 21 DOF's were used to model the interactions between the platform, WECs and the air pressure inside the chambers. Quasi-static approaches were used to represent the influence of the wind loads on the turbine.

Li *et al.* [49] proposed the Hywind-Wavebob-NACA 638xx Combination (HWNC) by integrating the Hywind SPAR [43] OWT with the Wavebob point absorbers [19] and tidal turbines [50]. Hydrodynamic and aerodynamic considerations were included by means of linear potential flow and blade element momentum theories, respectively. A multi-body dynamics approach was adopted for simulating mechanical connections and the mooring lines were represented using a lumped-mass approach.

Table 2: Comparison of numerical models for MPPs

No.	Platform	Aerodynamics	Hydrodynamics	Structural dyn.
1	SFC [38]	BEM	potential flow	multibody
2	STC [39]	wind drag force	potential flow	multibody
3	WindWEC [42]	BEM	potential flow	rigid body/FEM
4	C-HyP [45]	relative wind speed	potential flow	lumped mass
5	MERMAID [47]	relative wind speed	potential flow	rigid body
6	HWNC [49]	BEM	potential flow	multibody

A summary of the numerical modelling approaches discussed is presented in Table 2. It can be observed that a variety of approaches have been adopted for representing the aerodynamics aspects, ranging from a simple static wind drag force (generated by a body that opposes the flow of wind), to the more accurate blade element momentum (BEM) theory (where the blades are divided into elements and the forces acting on them are summed up together). As far as the hydrodynamics is concerned, all the models adopt a wave diffraction based potential flow approach, which is ideal for large structures. The structural dynamics aspects are modelled with different approaches and level of fidelity/accuracy. In a rigid body approach, the whole body is considered rigid and therefore there is no elastic deformation, while in a multibody approach, the system is comprised of several bodies linked by joints that control their relative motion.

The SFC and the STC mentioned above have been tested experimentally, at a scale of 1 : 50. The SFC consists of a semisubmersible floating wind turbine and three fully submerged rotating flap-type WECs. The PTO configuration of each of the WECs were physically modelled with the use of a shaft, two pulleys, a timing belt, two tensioners and a linear mechanical rotary damper with constant damping level during the execution of the tests [39]. The wind turbine was modelled with a redesigned small-scale rotor that rotates during the experiments. The quasi-static excitation, motion decay, response under regular and irregular waves, without and with wind were tested for and a good agreement was observed with numerical predictions.

The STC model was tested in two different basins to account for experimental uncertainties. Two model tests were performed to investigate the performance of the STC under the two survival modes in extreme conditions: when the torus is fixed to the spar at the mean water level and when the torus is fixed to the spar at a submerged position.The focus of the model tests was wave-induced loads and responses, and wind was also included to model the mean wind thrust on the wind turbine rotor [51, 38, 52].

The above mentioned previous European projects investigated the performance of platforms suitable for large wind farms of the order of 0.5 to 1 GW. There, however, arises a need to study the response of small MPP's capable of catering to the power requirements of remote and island communities, which might be substantially different from those already investigated.

2.2. Aquaculture

Aquaculture refers to the cultivation of fish and other aquatic organisms in a controlled manner, for human consumption. Marine aquaculture systems employ a variety of designs, based on the type of seafood harvested. They can be moored to the seabed, tied to a structure or towed by vessels [53]. Cage type structures anchored to the sea floor are generally preferred for finfish [54]. Shellfish cultivation is done either by bottom farming or by making use of lines suspended beneath floating bodies like buoys, rafts and longlines.

Aquaculture in more exposed, harsher conditions is perceived to be the next step, with a number of projects looking at suitable concepts, and a full scale pilot test facility represented by SalMar's "Ocean Farm1" [37], already in operation. The Ocean Farm 1 is a semi-submersible rigid cage of 110 m diameter, capable of housing up to 1.5 million salmon. Vessel type rigid floating cages or Havfarms [55], capable of withstanding 10 m significant wave heights are also being planned for use in the near future.

2.3. Combined ORE and Aquaculture

The Sea Star Spar [33] proposed a combination of a spar floating wind turbine and floating structures with sufficient buoyancy for the cultivation of finfish, shellfish or algae. Goseberg *et al.* [56] investigated the interaction between OWT structures and aquaculture systems by experimentally analysing the scaled model of a tripile supporting a 5 MW turbine, with a fish cage installed between its legs. Variations in flow velocities and additional loads on the substructure, arising from the presence of the cages were detected. Under the MARIBE project [57], different combinations of offshore wind, wave and aquaculture systems were identified, considering multi-use of space (MUS) and MPP criteria.

Viúdez *et al.* [58] proposed the use of a spar-type OWT to create an artificial upwelling of the nutrient-laden waters from the deep to increase the surface fish production. An experimental study on wave energy systems at Lysekil on the Swedish coast concluded that structural modification of the foundations (perforations, in this case) and other components could lead to enhancements in the fish population [59].

2.3.1. Control Strategies

Control systems form an integral part of any energy system. Coupling several ORE technologies and energy storage on a single MPP for aquaculture operations calls for a hybrid control system. This is due to the fact that while aquaculture requires a smooth, stable supply of power, ORE systems are highly dependent on their environmental source for power production. This can often result in periods of zero power production [60]. The existing scenario in control strategies for MPPs is reviewed in the following subsections.

2.3.1.1 Challenges of MPP control system

For an MPP combining ORE and aquaculture, while the latter can smooth the influence of waves and currents on the platform [61], it also has an impact on the layout of the power generation equipment [62]. Also, the interaction between the floating platform, wind turbine, WECs and energy storage (ES) devices, exists in many aspects such as the motion response, the dynamic loads and the control system, making the MPP a highly complex and coupled system.

The power supply of the MPP should be smooth and stable to meet the requirements of both the platform operations and the aquaculture system. The power transmission between land substation and the MPP also needs to be stable. As a result, power generation, ES and electrical equipment on the MPP need an overall power control and capacity management system. No comprehensive review of control technologies for MPPs currently exists. However, reviews on control of wind and wave devices [63], and control of energy storage (ES) systems [64], are useful for the present purpose.

Control systems for each ORE technology aims to operate the devices at their rated values by following an operating strategy, whilst maintaining safe operating conditions. The power generated by each technology depends on the renewable source cycle, leading to periods of zero power production. In an MPP, the combination of wind, wave and ES technologies can minimize the time of zero power production if shared control objectives are attained by means of a platform-level controller. These objectives can be classified as maximization of energy capture (wind and wave), regulation of generated power (wind, wave, ES), mitigation of structural loads for MPPs with large power capacity (wind, wave, platform), and reduction of unwanted platform swings and motions. For some types of ORE, estimation of the input can be of further benefit to the attainment of the control objectives, especially incident wave estimation for WECs [63].

The size of the MPP thus plays an important role in the definition of the control objectives. Promising wind/wave hybrid concepts estimate that the total installed capacity of around 10 - 20 MW would include 20 - 25% of wave energy, since energy efficiency of the WEC is much less than that of the wind turbine [65].

2.3.1.2 Management of power network and ES system

The control of the electrical system is often treated separately from the control of the mechanical systems. The MPP grid is different from a conventional grid as the former depends basically on a collection of inverters and synchronous and/or asynchronous generators. Each generator will have a control system to provide voltage and frequency regulation. A power network management strategy is therefore required to provide the operating states to the local electrical control systems and also to control power sharing and achieve network stabilization. The power network management is developed based on the MPP size and type of interconnection (*i.e.*, grid connected or isolated) [66]. Network stabilization and reactive power compensation can be further improved by the use of FACTS (flexible AC transmission systems) devices [67].

A detailed local electrical network (*i.e.*, including loads, cabling network, protection, switchgear, transformers and a power network management, operation and control system) definition/identification is still required; as its optimal sizing to meet load requirements with minimum investment and operating costs [68]. Conventional methods for resynchronizing the local network to the main grid and power flow control between the two grids can be used [69].

An ES device can be used to suppress fluctuations of ORE [70]. Cao *et al.* [71] proposed a battery energy management system (BEMS) strategy, and the point estimate method is used to solve the volatility of ORE generation. Osório *et al.* [72] studied battery pack modelling and health feature extraction methods for an ocean power station to reduce the number of battery charging and discharging cycles and dump load, and to improve the life of ES devices. Methods of multi-scale energy management have been proposed based on power generation/load forecasting, in which the multi-time scale energy management model is combined with daily scheduling [70] and real-time scheduling [73]. Further, physical constraints also need to be addressed for ES system.

2.3.1.3 Island/sea power integration

The integration of island/sea area ORE power is mainly based on micro-grid technology including AC, DC and AC-DC hybrid micro-grids. The DC microgrid avoids many problems such as the loop-current between multi-inverter, protection strategies of AC grids, which conforms better to systems with source diversity and load diversity [74, 75]. According to the availability of grid support, micro-grid can be divided into the grid-connected island power supply system and the remote isolated power supply system. With the remote isolated power supply, several demonstration projects have been completed and put into operation, such as the Dongfushan and Nanji islands in China [76, 77].

2.3.1.4 Island/marine micro-grid control and management

The micro-grid control system can be designed with different structures, *i.e.* the centralized control, the decentralized control and the hierarchical control. In the land-based and shore-based micro-grid demonstration projects, the centralized control is used more in Asia and the decentralized control mainly in Europe. The hierarchical model combines advantages of centralized and decentralized control, allowing better flexibility and scalability [78]. For the MPP control system, the use of hierarchical model is likely to be a better choice [79]. One recent successful example is the three-tier hierarchical management model applied in the marine micro-gird of China's Zhai Ruo mountain [80].

Grid planning has evolved from the realization of the grid-connected/off-grid function and the smooth transition process in early time (through classical control and various intelligent control theories) to the economical, reliable, high-quality, environmentally power supply. The planning and design of the island micro grid can be realized from single-objective optimization to multi-objective optimization. Life cycle cost, power supply reliability, power supply quality and other indicators have been considered in the optimization [76, 81, 82, 83].

3. Environmental Aspects

3.1. Environmental Impact Assessment

3.1.1. ORE

Boehlert and Gill [84] have highlighted the major ecological and environmental concerns accompanying the development of various ORE systems. The different forms of ORE extraction were considered in isolation and impacts were studied on the basis of a stressor-receptor framework. Here, the former refers to environmental features susceptible to change from ORE development and the latter stands for elements of the ecosystem that may respond to the stressor. Among the potential hazards were habitat loss, bird hits (from moving turbine components), acoustic and electromagnetic emissions. Best practice measures for the mitigation of the effect of WTs on birds have also been mentioned [85]. Some WTs were recently dismantled in China due to the severe impact on the bird migration [86], indicating the importance of site selection assessment for the construction of wind farms.

Several environmental impact assessment studies have been carried out on individual wind and wave energy concepts. The main concern for acousticallysensitive species such as marine mammals to date has been the construction phase of bottom fixed OWTs due to the widespread use of pile driving, with comparatively limited focus on sounds emitted by operational OWTs, let alone floating ones [87, 88, 89, 90]. Nonetheless, the ability of species such as harbour seals and porpoises to detect and react to the sound emitted by operational OWTs has been identified as a potential concern [91]. Marine fish and invertebrates may be similarly hampered in terms of communication masking and disturbance [92, 93], although there is presently no evidence of noise emitted by operational OWTs causing physiological damage in fish [94]. Offshore WECs might present a collision risk for diving species and can potentially change local oceanographic processes by extracting large amounts of incident wave energy [95].

In addition to the adverse impacts, the potential benefits of ORE systems to biodiversity have also been suggested [96]. These include the potential for ORE structures to act as secondary artificial reefs to aid in the enhancement of fisheries and rehabilitation of marine habitats [97, 98, 99]. Floating ORE installations also have the capacity to act as local fish aggregation devices [97, 100]. As fishing around ORE installations is often prohibited, such areas can serve as miniature impromptu Marine Protected Areas (MPAs) [101]. Potential effects on wild species, as well as associated commercial/recreational fisheries, of this inadvertent protection presently remain poorly understood.

3.1.2. Aquaculture

At-sea aquaculture, particularly those involving finfish, can have multiple impacts on the surrounding marine environment (summarized by Tett *et al.* [102] focusing on Atlantic salmon). These include, in no particular order:

- impacts on wild fish stocks through increased parasite and pathogen densities [103, 104, 105, 106], competition between wild and escaped fish for resources [107, 108, 109], and genetic dilution of local wild fish stocks through interbreeding with escaped fish (an acute problem for salmonids [110, 111])

- degradation of surrounding seafloor communities through deposition of organic waste [112, 113], reduction in dissolved oxygen [114], eutrophication [115, 116, 117] and dispersal of various chemicals [118, 119]

- direct and indirect impacts on large mobile species such as marine mammals and seabirds, including shooting and exposure to loud underwater noises (to prevent depredation of cultured fish [120, 121]), accidental entanglement in nets and moorings [122], and displacement from potentially important habitats due to fish farm-associated activities [123, 124]

Some positive impacts on particular species include provision of food and shelter for wild fish, and foraging and resting opportunities for marine mammals and seabirds (although this increases the risk of further negative interactions outlined above). Some of these impacts are indirectly driven by the inshore, sheltered nature of the sites where finfish aquaculture has developed to date. There is pressure to expand the sector into more exposed, offshore locations, which may reduce or modify some of the aforementioned impacts (*e.g.* eutrophication, attraction of wild fish) due to greater exposure and stronger water movements; however, the nature of these changes, if any, remains poorly understood and difficult to predict at present [125].

As for the considerable amount of biogenic waste such as organic wastes and inorganic nutrients that are generated in the fish farming process, trash fish (small fish of low commercial value) feeding showed more severe cumulative impact to the aquatic and sediment environment than pellet feed [126, 127, 128]. Trash fish is still a popular traditional feed for marine carnivorous fish in China and many Asian countries, and this practice is likely to persist for some time despite farmers are encouraged to use pelleted feed to minimize the environmental impact. Field monitoring, lab tank experiment and bioenergetics models were both applied to quantify the wastes generations and the environmental impact [128, 129, 130, 131, 132].

3.1.3. Combined ORE and Aquaculture

While ORE and aquaculture have matured as separate industries, the environmental impacts when these sectors are combined within a single site are very poorly understood and almost entirely based on theoretical projection of the single industry impacts on to a multi-use site. Much of this understanding has come from the European funded projects mentioned in section 1.3 and through application of cumulative effects assessment methods [133, 134].

The TROPOS project made use of an impact assessment approach to study the effects of combining the two industries, as opposed to a single use scenario [135]. To allow a direct comparison, a semi-quantitative scale was used for each impact category. This methodology used the difference between the impacts of a single use platform compared to those of a multi-use platform, and combined the impacts either on a an additive value of through the use of which ever value was highest, and this was conducted for both negative or positive attributes. It was concluded that while the impacts are similar for the single and multi-use approaches, the latter had the advantage of integrating diverse activities in a common location.

The H2OCEAN project was recognized that the impacts of different sectors may combine, and that the cumulative effects may reach thresholds of impacts, therefore recommending a comprehensive cumulative impact assessment [136]. Understanding of the impacts from multiple sectors of the system was limited to recommendations on the location of the living quarters, and their outfalls, to prevent potential conflicts [137].

Within the framework of an expert opinion approach, the MERMAID project identified a number of scenarios involving different combinations of aquaculture and ORE systems. Common environmental benefits, such as structures providing a refuge for wild fisheries species and operational constraints like increased bio-fouling, were also listed. A framework for risk analysis was also defined, including internal environmental interactions between the biota and different types of foundation and material [61].

3.2. Ecological Modelling

Modelling the effect of the installation of an MPP system in a marine ecosystem is challenging. On a large spatial scale, deployment of offshore structures for ORE generation will lead to exclusion zones, limiting the access to the area for several users such as shipping, fishing and tourism [138, 139, 140, 141]. Such infrastructure can also underpin development of 'artificial reefs', supplying nursery areas and feeding grounds for fish species [142, 97]. Species larvae and juveniles can disperse to the surrounding areas leading to a 'spill-over effect', enhancing local production [143, 144, 145]. These infrastructures can also create new substrates for benthic organisms [146, 99, 147]. The creation of new benthic habitats can lead to either displacement or attraction of benthic species in the local area, resulting in changes to local food-web dynamics with both positive and negative impacts on species distribution and abundances [148, 149, 150, 151].

Aquaculture associated with the MPP structure can increase the productivity in the water column and on the surrounding sediment (detritus enrichment): depending on the characteristics of the surrounding environment, this increased productivity can lead to large-scale impact, attracting top-predators species [152], and small-scale impact, affecting benthic faunal communities, important food source for many species including those of commercial importance [83].

'Exclusion zones effect' and 'artificial reef effect' can therefore lead to both synergies and conflicts with other marine users, notably the fishing industry [153, 154, 155]. Modelling small-scale impacts will require a high resolution of the model spatial grid with associated high computing power [141, 83].

Ecosystem-based approaches are necessary to investigate the cumulative effects of human impacts on marine ecosystems [156, 157, 158, 159, 160, 161, 144, 162, 145, 163]. Ecosystem models have proved to be a powerful tool for monitoring natural variability, assessing impacts of natural and anthropogenic environmental changes and advising management measures [164, 165, 161, 166].

The Ecopath with Ecosim and Ecospace (EwE) modelling approach has been considered one of the most suitable tools for evaluating the direct and indirect effects of anthropogenic pressures on large spatial scale ecosystem dynamics [167, 168, 161, 169]. EwE models have been successfully used to evaluate how these pressures cascade through the food-web. For example, changing in the spatial distribution of top predators (cetaceans, large fish and seabirds) will affect the entire marine ecosystem through top-down control pathways [170, 152]. Similarly, changing of primary productivity can cascade through the food-web by means of bottom-up controls [144, 145] as well as environmental drivers [144, 171]. The use of Ecospace to assess cumulative impacts of these effects have been exponentially increased since the later development of this software [172, 169, 144, 173], with new capabilities of coupling the spatial model with external spatial data (e.g. spatial habitats and hydrodynamic drivers). The EwE model has also been applied in the Bohai Sea, the Yellow Sea and the East China Sea to describe the energy transformation between trophic levels [174], to demonstrate the fishery resources declining due to overfishing [175] and the predominant fish species variation in the past decades [176, 177, 178].

4. Socio-economic aspects

Socio-economic is a term that defines the effect of a project - its development, operation and decommissioning, on the local population, or the society. There have been numerous studies on the socio-economic impacts of ORE and aquaculture, mostly undertaken on the basis of stakeholder interviews and surveys. The main inferences are listed below.

4.1. ORE

4.1.1. Offshore wind

Despite the advantages that offshore wind offers, several socio-economic drawbacks have been identified. A particularly problematic factor hampering the development of onshore wind farms, is public opposition arising from social concerns, such as visual pollution and the impact of noise [179].

Even as offshore wind farms are considered to be less intrusive than those onshore [180], public perception of the visual impact, notably shadow flicker and the impact on seascapes, remains an important concern [181].

In addition, whilst the underwater noise caused by the operation of wind farms has recently been shown to be of very low level and probably insufficient to cause any significant environmental effects [182], the noise which is created by the impact piling required for the foundation installation of OWTs has been found to be of extremely high level [183, 184, 89]. Such issues represent a challenge for the industry, planners and regulators as they can influence public opinion, which studies have observed to be dependent on demographics [185], with for instance, older people being more concerned with visual pollution [186].

Opposition also arises from concern over the fate of the local fishery industry [187, 188]. On the other hand, support for OWT projects arise from the understanding that they provide a non-polluting energy source, capable of generating jobs and contributing to the economy [189, 190].

4.1.2. Wave energy

The emergent nature of WECs, and the lack of commercial-scale deployments, results in uncertainties surrounding their potential positive and negative socio-economic effects and impacts. However, studies have highlighted a range of socio-economic impacts associated with WEC developments typically including demography, employment and regional income; sea and land use; aesthetics; infrastructure; socio-cultural systems and implications for other maritime activities such as fisheries, tourism and recreation [191, 192, 193, 194].

In addition to the benefit of providing a new source of electricity from a local, low carbon energy source, WEC developments will potentially bring economic benefits including the creation of jobs, the development of new supply chains and investment in infrastructure required to support such developments [194, 195]. However, uncertainties regarding the delivery of such benefits, and the potential displacement of jobs in different sectors have been identified as concerns [194]. Notably, WECs, like any other marine development activity, inevitably cause a change in the use of the ocean space at the deployment site that is likely to disrupt or displace the activities of other users of the area. Of increasing concern are potential restrictions on the accessibility and use of the surrounding marine space, introducing the risk of conflicts with other marine resource users and stakeholders [194, 196, 197, 198].

As with environmental concerns, the socio-economic effects and impacts of WEC will vary with the stage (construction, operation and decommissioning) and scale of the project and will depend on the location, communities, economy and environment in that area. For example, concerns regarding the ability of communities to adapt to changing demand for new services, skills throughout the WEC project lifecycle are emerging [194]. Furthermore, whilst some studies have argued that unlike wind energy, WEC developments do not cause visual pollution, as they are often located at great distances from the coasts and have mostly submerged configurations, this may not be true with differing WEC designs, deployment sites and community perceptions of the marine environment [199].

A further concern is that WECs may also provide non-market benefits, such as providing coastal protection benefits, they may negatively impact upon the ecosystems services and provisioning services, such as fisheries and the cultural services provided by the marine and coastal environment [194, 200]. Such issues are of particular concern because WEC developments are proposed in rural coastal locations and islands, where strong cultural ties to the marine and coastal environment exist and may result in community opposition [194].

Indeed, emergent research investigating such issues has identified divergent views on the socio-economic benefits and appropriateness of wave energy development [194]. For example, studies have attributed public support to wave energy being perceived as a renewable source and its capability to boost the local economy, without affecting established activities like fishing [201, 191]. Elsewhere, perceptions and support for WEC and ORE have been associated with place attachment, community pride and the ‘symbolic fit’ of place and technology [194, 202]. For example, Alexander *et al.* [141, 203] found broad support for WEC amongst Scottish fishers. However, the nascent nature of WEC technologies and deployment means that many are yet to form their views and opinions [191].

With community buy-in and support being vital to WEC deployment, there is clearly a need to maximize community benefits [194]. For example, some communities have questioned the potential benefits of WEC developments, which may result in increased electricity prices or taxes if subsidized. Thus, calls for wealth distribution and community benefit schemes, similar to those associated with other industries, have been made [194, 204]. These may range from community payments, to new forms of business models, including shared or community owned schemes [194]. The embryonic nature of WECs and the lack of commercial deployments also mean that there is a paucity of empirical research investigating their real world socio-economic impacts.

4.2. Aquaculture

Based on the available literature, Krause and Mikkelsen [205] have attempted to capture the socio-economic aspects of aquaculture, in a multi-use perspective. Socio-economic analysis have always taken the back seat, with regard to the development of aquaculture activities, the focus being on technical and biological issues [206]. Further, exiting studies concentrated on the influence of salmon, shrimp and seaweed farming [207]. Socio-economic studies for aquaculture have to be tailored to suit the local economic and geo-political settings and the outcomes cannot be generalized. For instance, in a study on risk perception and management in Norwegian aquaculture, fish farmers were more concerned about the future prices of their stock and potential disease outbreaks. On the other hand, they were least bothered about aesthetic considerations and repugnance to the public [208].

While food and jobs are the main direct socio-economic benefits from aquaculture, it has to be noted that in many Asian countries like Vietnam and Bangladesh [209, 210], the fishermen community is struggling to survive with the generated income. Further, the negative effects of aquaculture have been difficult to quantify, mainly due to the lack of knowledge and awareness among the consumers [211]. The recent decades have witnessed large degradation of the coastal marine environment and its resources in many areas, at least partly due to an unprecedented growth of the aquaculture industry, coupled with the absence of proper national and international regulations, policies and management strategies [212, 213].

There are several studies on the sustainable development of offshore aquaculture, wherein the society, economics and environment are given due consideration [214, 215]. Proposed aquaculture developments have been known to cause concern among local fishing communities [216]. Often, the concerns involve potential risks pertaining to the aquaculture development [217].

5. MPPs and Risk

The offshore environment is associated with high technical risks arising from the mechanical forces, corrosion, biofouling, extreme conditions and unreliable moorings [13].

Research investigating such risks is emerging, with the MARIBE project considering the technical and non-technical challenges associated with MPP including risk perceptions of new technologies and their combinations [14].

A simple methodology for assessing the risks associated with MPPs, considering operation, economic, environmental, socio-economic, financial, political and health and safety risks across the different phases of a project was presented [14].

The MERMAID project utilized the Policy, Economic, Social, Technical, Environmental and Legal (PESTEL) approach (also known as PESTLE), along with stakeholder analysis to gain a clearer understanding of external factors affecting future MPP developments [11]. This identified legal and policy, social, environmental, technical and economic issues as presenting key obstacles to MPP.

Legal and policy obstacles identified included complicated bureaucracy, poor dialogue between public institutions and difficulties identifying responsibilities for permits, and a lack of codes and standards [11]. Social obstacles refer to potential conflict with near-shore and offshore fisheries, tourism and shipping routes.

Further, activities that change the marine landscape were deemed socially unacceptable by stakeholders. However, some perceived social obstacles (*e.g.* anchoring issues) stem from a current lack of experience and understanding of ORE installations.

Other concerns are about insurance (costs may increase once the potential types of accidents insurers will have to cover become clearer) and the financial feasibility of combining some activities (*e.g.* mussel and seaweed farming with offshore wind farm (OWF)), due to the reluctance of OWF operators to share space due to potential risks arising from multiple uses.

While new jobs and revenue streams are obvious socio-economic benefits of MPP projects, there was also evidence of potential conflict with fishing communities and between wave energy production and energy suppliers, equipment and machinery, and marine transport. In particular, the offshore wind industry is concerned about potential risks (*e.g.* collision and corrosion) arising from MPP developments [218].

Such findings highlight the need for further research, investigating the potential socio-environmental-policy-technological risks, opportunities (*e.g.* new business models), challenges (*e.g.*, barriers, and enabling mechanisms), trade-offs associated with MPPs, and their governance. Given the complex and multifaceted emergent properties, and trade-offs associated with the multiple activities that MPPs comprise, new trans-disciplinary methods, adopting systems approaches resilience-thinking, will be vital to overcome the limitations associated with traditional single discipline approaches [194, 219].

This will require consideration of critical systems functions, interactions and inter-dependencies, and their uncertainties, together with levels of robustness and resilience of the MPP and its component systems, across its life-cycle, under a range of conditions including low-frequency high consequence extreme events (e.g. typhoons and storm surges) [219]. Furthermore, greater consideration of cumulative effects, requiring new approaches to overcome recognized limitations in CEA practice are required [133, 134]. Such studies will support the identification of priority risks and monitoring, management and mitigation measures to reduce MPP risks and vulnerabilities.

In parallel research assessing the socio-environmental impacts and benefits of MPP is urgently required. Critically this should include consideration of societal acceptability and values, potentially affecting MPP development, and strategies for optimizing their benefits and reducing the risk of conflict. For example, siting MPP further offshore may avoid nearshore conflicts with sectors such as tourism and navigation [12]. This in turn will requires exploration of the governance challenges associated with MPP.

Here, it is argued that MPPs and co-location of activities could result in the development of a common regulatory framework, resulting in more co-ordinated marine spatial planning and simplified licensing procedures [13]. In parallel, with research highlighting a wide range of potential legal issues surrounding ORE [220], studies exploring the legal implications of MPP, notably liabilities and the potential need for new forms of business model, will be of importance to the sector.

6. Overview and discussion

As previously stated, due to the scarcity of references analyzing MPP systems, the scope of the review has been expanded also to research works analyzing single energy source systems/single aquaculture systems.

In the synoptic Table 3, the references cited have been classified against the type of system analysed:

- A ORE systems extracting energy only from one type of energy source (single purpose);
- B Aquaculture (only) systems;

Table 3: System classification of references

System → Aspect ↓	A. ORE systems – single energy source	B. Aqua--culture systems	C. MPP without aquaculture		D. MPP with aquaculture	
Techno--logical	[221, 222, 20, 63] [223, 224, 225]	[53, 54, 37]	[16, 12, 18] [19, 23, 25] [26, 27, 221] [222, 21, 24] [28, 29, 30] [38, 39, 42] [45, 47, 49] [227, 228, 67] [68, 225] [229, 230]	[13]	[56, 58] [59, 33] [218]	High Level [10, 25] [27] Detailed [11, 57] [226, 61]
Environ--mental	[84, 85, 91] [94, 95, 96] [97, 98, 99]	[53, 231] [232, 233, 234] [235, 236]	[135]		[135, 136] [137]	
Socio--economic	[15] (Wind) [7, 179] [180, 181, 185, 186] [190, 187, 188, 189] (Wave) [199] [201, 191] (Policy) [2, 3]	[9, 205, 206] [207, 208, 209] [210, 211] (Policy) [238]	[13, 135]		[12, 13] [237, 100] [135] (Policy) [239]	

C MPP coupling offshore systems extracting renewable energy from two or more sources, but not coupled with aquaculture system/s;

D MPP coupling offshore systems extracting renewable energy from two or more sources, including aquaculture system/s;

and against the aspect/s considered, i.e. if mainly concentrating on the technological (engineering) aspects, the environmental impact aspects, the socio-economic aspects, or all of them.

6.1. Main considerations on the literature reviewed

Most of the research has been focused on the technological aspects of the MPP systems, followed by the socio-economic aspects, and then the environmental impact aspects. This can be explained by the Technology Readiness Level (TRL) of the research conducted in this area, which in most cases can be assessed as between TRL 2 amd TRL 6, if the TRL scale used by Horizon 2020 EU funding scheme is adopted, reported in Table 4. As it can be seen, even if it is not the only aspect, from TRL 1 to TRL 6 the focus is on the technological aspects.

Table 4: Technology Readiness Level [240]

TRL 1	Basic principle observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment
TRL 6	Technology demonstrated in relevant environment
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment

An important first consideration following up from this one is indeed that, despite the substantial advantages obtained if both the environmental and the socio-economic aspects are considered from the early stage of the technology development, the need to adopt a multidisciplinary approach is still not common practice even for commercially mature systems, with only few noticeable examples [11, 14, 57, 61, 226].

The second consideration is that the research done on MPP has been much more focused on the so called ‘hybrid’ ORE systems, i.e. coupling wind, wave, and tidal systems, but considering the direct coupling or the close co-location of aquaculture systems in very few cases, especially when considering the technological aspects. The Blue Growth EU-funded projects have started to address this gap in knowledge, and MERMAID [27]), but have also highlighted the several multidisciplinary challenges to be tackled.

The third observation is that these European projects had been focusing on large commercial scale installations, MPP farms, consisting in installed capacities of the order of hundreds of MW to GW, connected to the grid and, whenever considered, aquaculture systems of commercial scale. Nonetheless, as demonstrated by some pilot projects in China (Daguan [221], Dawanshan [222], and Sehngshan [222]), there is a strong potential for small scale MPP to serve remote, isolated communities, providing not only a sustainable, safe, affordable source of energy, but also socio-economic benefits such as food and jobs.

Furthermore, also in the EU there is a growing research interest in coupling sustainable source of energy to offshore aquaculture facilities [36, 241]. The research on small scale MPP can certainly learn and build upon the ones done for large scale MPP farms, but it is likely that there will be some specific challenges. For example, the scale of the environmental impact is completely different, the metocean conditions will have a higher impact on the dynamic response of the MPP, and the dynamics of the different systems (wind, wave, solar, aquaculture) may be more strongly coupled. There is certainly a need for further research.

7. Conclusion

An emerging interest in the development of multi-purpose platforms, exploiting the synergies among ORE and aquaculture industries, has been observed over the past decade.

Based on this analysis, the following main points can be derived, which also constitute a statement of the current gaps in knowledge:

- In general, there is a scarcity of literature specifically on MPP systems, probably due to this technology's low TRL level, and the lack of full scale, but also small scale outdoor prototypes;

- Therefore, at the moment, this area of research has to rely on single-purpose, single discipline studies to develop a multidisciplinary analysis framework for MPP systems: the present article aims at providing an overview of the available material to develop such framework;
- If the number of sources on MPP can be considered proportional to the research effort, most of the effort so far has been allocated to the technological aspects (again, probably due to the low TRL level), while the socio-economic and environmental aspects have been investigated to a lower extent;
- The adoption of a multidisciplinary approach is still not common practice even for more mature, single-purpose offshore systems, with only few noticeable examples;
- The majority of the literature focuses on a small subset of MPP, coupling only different ORE devices, but not integrating or co-locating aquaculture systems, with only relatively few recent EU-funded projects that started to address this gap in knowledge;

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