Floating wind and wave energy devices: applications, synergies and role in decarbonization in Portugal

Craig White, Ana A. D. Carrelhas, Luís M. C. Gato, Juan C. C. Portillo and José J. Cândido

Abstract—**Floating offshore wind and wave energy are both promising marine renewable energy technologies that are still at an early stage of development. This paper reviews synergies between the two technologies that can be mutually beneficial and facilitate the path to commercial exploitation. The analysis focuses on three different types of combined wave and wind systems: Co-located arrays, hybrid systems and island systems. The decarbonization potential of co-located systems is discussed. Existing carbon emissions from marine technologies are compared and how synergies can achieve these reductions are explored. A case study is presented to calculate the impact of multi-purpose platforms on the Portuguese energy system. Portugal was chosen because it has an excellent climate for marine resources, deep waters, positive political support for renewable marine energy and previous success in deploying first technology demonstrators for floating wind and wave energy systems.**

Index Terms—**Hybridization, floating wind and wave devices, synergies, wave energy, decarbonization potential.**

I. Introduction

A full transition of our current carbon-wedded energy system is essential and must happen fast. This can be achieved through a highly electrified, low-carbon energy system, connected via a smart grid that uses appliances and energy storage to match temporal and variable renewable energy generators. This can allow high levels of Variable Renewable Energy (VRE) into the grid to help decarbonise the power system, without destabilisation and causing polluting dispatchable generators to regain control, further raising emissions.

Renewable development is essential but higher levels mature distributed VREs including solar and onshore wind will impact and cause conflicts with other essential land uses: such as arable land for food production, housing and recreational spaces. Global populations have also not yet reached their peak, increasing pressure on areas for food production increase combined with less space available for food production due to climate caused droughts and soil degradation.

Marine renewable energy (MRE) technology can solve this potential conflict. Operation occurs away from population centres, with clean energy delivered through export cables to demand centres onshore. Of these, Floating Offshore Wind (FOW) and Wave Energy (WE) are two of the most promising emerging technologies but they must accelerate development through Technology Readiness Levels (TRLs) if they are to compete with other forms of better-established MRE, such as bottom-fixed offshore wind (BFOW) which has seen rapid growth and now competes with conventional power plants. If FOW and WE can achieve commercial viability and prove technology at scale, the potential marine resource is vast. Deep water MREs must be deployed to meet future low carbon energy systems [1].

Even though the sector is in relative infancy, there is strong competition from bottom-fixed offshore wind (BFOW), which has seen with phenomenal growth since the first wind farm was installed in 1991 [2], and has grown almost 30% per year from 2010-2018 [3].

An issue arises with larger numbers of wind turbines constrained to near-shore coastal zones and shallow waters, with the cheapest and most prevalent monopile foundations limited to around 30 m of water depth [4]. Transitional water substructures can operate in depths of up to 80 m, but higher costs have limited their deployment.

FOW & WE can operate in these deeper waters and open up new areas of generation and economic opportunity, with 80% of the wind resource located waters greater than 60 m in depth [5]. Mooring lines and platform technology has already been proven in the oil and gas industry over multiple decades and has survived extreme storm conditions [6]. These offshore areas also boast stronger and more consistent wind resources, leading to higher performance, lower turbulence, better capacity factors and higher energy generation [7]. FOW & WE can locate away from heavy marine traffic and reduce visual impact, with no expensive heavy-lift equipment and can be towed for port-side assembly and repair. Extensive experiments at scale plus high quality numerical modelling has allowed concepts to reach prototype deployment in harsh marine environments [8].

FOW & WE operate in similar marine environments

This research was partially supported by the Portuguese Foundation for Science and Technology — FCT, through IDMEC, under LAETA, project UIDB/50022/2020.

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Digital Object Identifier:
https://doi.org/10.36688/ewtec-2023-413

and share common goals in developing out of their current infancy into mature and widespread technologies. Synergies can be defined and implemented to maximise the compatabilities that exist between the two technologies, plus exploiting the strengths of each technology that can help offset the weaknesses of the other. FOW is currently further ahead in terms of Levelized Cost of Energy (LCoE) and TRL level, and can aid WE through shared electrical infrastructure and O&M methods. WE also has multiple benefits that can aid FOW, though the co-location of WECs that can protect FOW devices and increase weather windows for servicing. Hybrid devices that can increase electricity generation whilst damping the wave action on a device. Positive interactions and co-operations such as these can help accelerate development and also help to lower the carbon content to boost the attractiveness of these new industries.

This paper aims to analyse the possibilities that may rise from combining offshore wind and wave technologies. First, the current status of both technologies will be assessed, through standout designs and deployed examples. Secondly, combined wave and floating wind potential designs are analysed. Thirdly, the decarbonization potential will be discussed, comparing existing carbon emissions of marine technologies and exploring ways that synergies could offer reductions. Before conclusions are drawn, a case study is presented to calculate the impact of multi-use platforms on the Portuguese energy mix. Chosen as Portugal boasts an excellent marine resource climate, deep waters, positive policy support for MREs and also past successes with the deployment of initial technology demonstrators for FOW & WE devices.

II. Current status of wind and wave floating technologies

A. Floating wind energy technologies

Floating Offshore Wind (FOW) has developed into four main platform designs, which have progressed at varying rates and are currently at different Technology Readiness Levels (TRLs). The most successful platform types have achieved progression through TRL stages up to pre-commercial array (TRL 9). This has been achieved across various platform types by setting new records for capacity factors that outperform competing technologies such as BFOW [9]. The projects have also demonstrated through build-out rapid LCoE reductions and by proving that the technology can withstand harsh marine environments.

Floating platforms can be categorized by stabilisation methods that offset external loading forces acting upon the structure [10], however in reality all designs are on a spectrum that achieve stability through a combination of methods [8]. It is of great importance to maximise stability, as unlike floating structures in the oil and gas (O&G) industry that mainly consider wave loading, FOWTs have to be designed to withstand both aerodynamic and hydrodynamic loads [6]. Floating structures are site specific, with an optimal design depending on the seabed type, water depth, plus wind, wave and current climate. The three main types of platform are listed and analysed in the following subsections.

1) Mooring line stabilised: Tension through the mooring lines creates a restoring moment and maintains stability, resulting in reduced platform size and mass. The World's first ever FOWT to be deployed and field tested was a TLP, operated in 113 m water depth off the coast of Italy from 2007-2008 [11]. The prototype was one of the only FOWTs to feature a two-bladed rotor and gathered valuable test data on FOW feasibility. However, since the initial demonstrator no subsequent units have been deployed, with GICON now developing a new modular Tension Leg Platform (TLP) that can be assembled without extensive port side infrastructure and uses a gravity anchor for seabed attachment [7].

2) Ballast stabilised: Righting moment created with a centre of gravity below buoyancy, with a slender cylindrical design which gives strong resistance against heave, surge, and sway motions [4] which could make this design suitable for signifiacnt wave environments. Initial testing of the spar buoy in tank conditions conducted in Japan in 2009 with a 1/22.5 scale model [8]. The Hywind Demonstrator was the first large scale FOWT, with a 2.3 MW Siemens Wind Turbine (WT). The concept was installed 10km off the Norwegian coast in 2009 in 210 m water depths, which are suitable to the large draft of the design. The demonstrator was equipped with over 200 sensors that allowed the loads acting on the structure to be accurately recorded for numerical analysis [12]. This approach allowed for large quantities of data to benefit the control and optimisation of the demonstrator, but also to benefit of future concepts, especially for early numerical modelling, digital twins and to accelerate low TRL projects. Owing to the success of the prototype, with no significant failures, the World's first floating wind farm, Hywind Scotland, a 30 MW pre-commercial array followed off the coast of Peterhead, Scotland. The array consists of five 6 MW WTs and has been in operation since 2017, delivering power to the Scottish grid through a 25 km export cable [13]. The Hywind Tampen project will also feature spar buoy platforms, but of concrete design and when operational in 2025 will be the Worlds largest wind farm at 88 MW [14].

3) Buoyancy stabilised: Buoyancy stabilised, with the Semi-submersible design the most prominent. The design is more susceptible to wave action and heave motions due to larger platform size, most but also conducive for hybrid WEC platforms with deck space. The first prototype was developed by the University of Maine [11], scaled to 1/8 normal size and rated at 20 kW. The prototype was the first grid-connected FOWT in the Americas, operating from 2013-2014. Principal Power tested their WindFloat concept at a 1/105 scale prototype which recreated 100 year wave scenarios in 2010 [8]. Successful tank tests lead to a full scale demonstrator located 15 km offshore of Viana do Castelo, Portugal. Siting far offshore caused the design to withstand and survive 17 m wave heights and 40m/s wind speeds, demonstrating the reliability of the platform [15]. The prototype was then success-

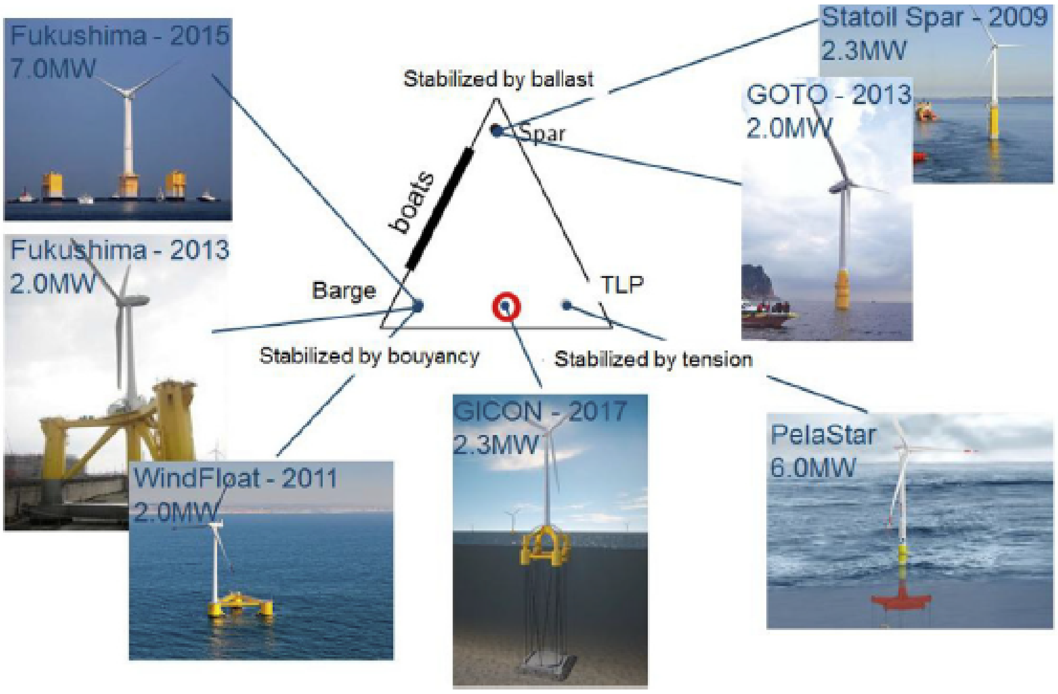

Fig. 1. Floating concepts and their position on the stability triangle [7].

fully decommissioned, retrofitted and transferred to Scotland for redeployment. A pre-commercial array was then installed in 2019, using three 8.4 MW turbines which are now powering 60000 homes [16]. From the initial success of the experimental scale model and prototype, rapid build-out and project expansion has caused the semi-submersible to be the most popular platform in use, with two projects commissioned and operational, plus six more in development worldwide. Once all fully commissioned, these platforms will be supporting 1.303-1.353 GW of floating wind power [17].

B. *Floating wave energy technologies*

Ocean waves are recognised as being a promising source of renewable power to generate electricity [20], although the diversity of devices under development indicates the current immaturity status of these technologies [21]. Unlike large wind turbines, more than one wave energy technology is likely to become commercially mature depending on the location (shoreline, near-shore, offshore) and water depth.

Principles of physics and engineering factors have led to the development of a great diversity of wave energy converter (WEC) concepts [21]. Most WECs are designed to have one or more natural frequencies matching that of the prevailing incident waves. This provides the means for the system to operate in resonance, with large motions relative to the water free-surface, enhancing power extraction from the waves. Resonant WECs are able to extract energy from wave crest lengths that may be larger than its characteristic dimension. The size of these devices is then related to the frequency of prevailing high energetic ocean swells which limits the unit power of point absorbers to hundreds of kilowatts or few megawatts [22]. Farms with a large number of devices are then needed for bulk power production.

WECs designed for resonance include two main groups: oscillating water column (OWC) devices and oscillating body devices.

OWC devices have no moving parts below the water level, see Fig. 2 (a). An OWC consists of a fixed or floating partially submerged pneumatic chamber, open at the bottom, where the air above the free-surface is alternately compressed and decompressed by the oscillating motion of the water column due to the action of the waves [23]. This produces flow through an air turbine that drives an electrical generator. The air turbine (usually a self-rectifying air turbine) and the generator compose the power take-off (PTO) system. Self-rectifying air-turbines rotate in the same direction independently of the direction of the airflow have been the preferred solution to equip large OWC devices [24]. This avoids the problems raised by the size of the ducts and corresponding system of rectifying valves that cannot be operated with a fast response time.

Oscillating-body type WECs consist of floating or submerge bodies reacting against a fixed structure, the sea bottom, or another floating body [25], see Fig. 2 (b). Energy is extracted from the motion of the single oscillating body or from the relative movement between two or more floating bodies. The most frequent PTO systems in this class of devices are linear electrical generators and oil and water hydraulic systems that drive conventional rotating electrical generators [26].

Non-resonating WECs include over-topping [27] and membrane pump devices [28], see Fig. 2 (c). Like wind turbines, multi-megawatt non-resonant WECs can be designed by increasing its size. Over-topping devices are designed to increase the wave height by concentration and or by running-up an inclined surface for

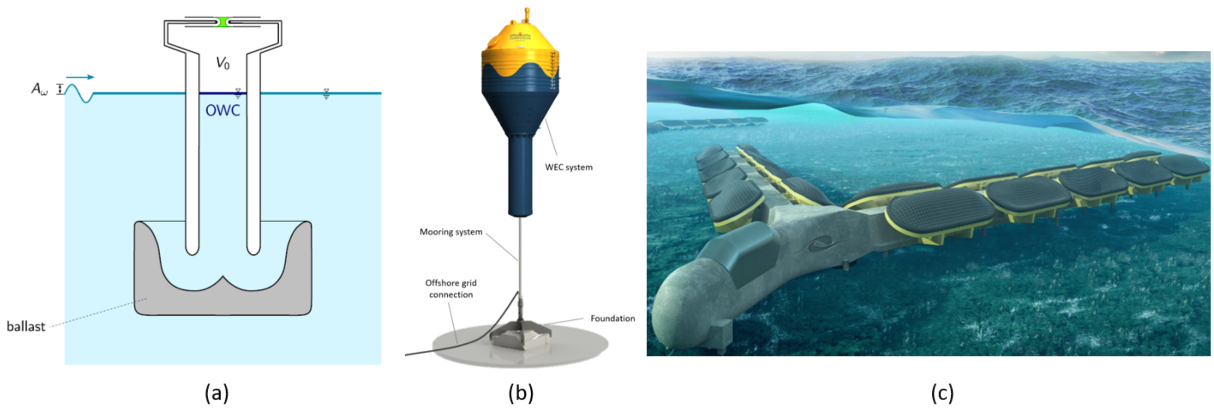

Fig. 2. Schematic representation of: (a) OWC devices [18]; (b) Oscillating Body (in this case is a CorPower device); (c) Non-resonating WEC (in this case is a mWave Bombora device) [19].

water to be spilt off to a reservoir. The water then passes through a hydro turbine generator set to produce electrical power similar to a conventional low-head hydropower plant [29].

Although a large number of WECs have been tested at sea, either as a large model or as a prototype, the variety of WECs still being proposed and tested shows that new developments are needed for the technology to reach the market. Above all, there should be more focus on testing in real conditions over long periods of time to test both the hardware and the software and build investor confidence.

III. Combining wind and wave floating technologies

In this section, the categories of combined wave and wind technologies are analysed, their benefits and critical points, and the markets that could promote the use of this two-in-one technology.

A. Classification of combinations of wind and wave floating technologies

The combination of wave and wind devices can be broadly grouped into three categories of systems [4]: 1) Co-location; 2) Hybrid; 3) Island.

1) Co-location: Separate FOWTs and WECs that are either merged array or separated and share common infrastructure such as export cables, an O&M port, and vessels. There are different typologies such as: (i) a substation and export cables are shared by a WEC and a FOW array, which are located next to each other; (ii) Along one or two sides of a FOW farm that face the predominant wave direction, forming an outer barrier. Wave energy is absorbed by the peripheral array, resulting in a smaller inner lagoon; (iii) WECs and FOW devices are evenly distributed across a combined hybrid farm; (iv) WEC devices are placed in areas of a mixed farm where energy generation is optimised, or they reduce wave action and loading on FOWT structures.

2) Hybrid: Multi-purpose platforms may consist of either a wind turbine integrated onto a floating WEC, or one or more WECs integrated into a FOW device. As wave energy dissipates in shallow waters, bottom-fixed structures such as monopiles and jackets can reduce the energy capture of their hybrid WEC device due to being constrained by shallow depth. In deeper areas where the seafloor has not yet interacted, hybrid combined devices with FOW can slow down the wave resource and maximise the opportunity for the combined devices to absorb maximum energy.

3) Islands: Larger multipurpose systems with multiple wind turbines, wave energy converters and there is also the potential for energy storage, O&M operations and shared electrical infrastructure with other offshore VRE projects. Larger offshore structure could broaden the range of wave energy devices that could be used, including OWCs to maximise potential energy capture.

B. Synergies (benefits)

The combination of wind and wave devices brings with it a whole range of advantages that could increase the amount of energy generated and reduce costs (and therefore the LCoE).

1) Shared costs: (i) The same grid infrastructure; (ii) The foundation may be shared resulting in cost-reductions when compared with separate projects; (iii) O&M and installation processes using common technicians; (iv) equipment that is needed for assembly, operation and disassembly, such as vessels are a must for both technologies; (v) in the case where the WECs are distributed in such a way that they are used as shields for the WTs, it implies that the weather windows for O&M are increased [31], [32].

2) Increase the produced electricity: Waves are more predictable when compared with wind [24], this would result in improved forecasting of the produced power [31] and avoid disconnections on the electric grid. Depending on the locations and on the type of combination of wind and wave devices, there could be an increase in available power output [18] and/or production occurring in different time-steps (when there is no wind, production via the waves is still possible and vice-versa) [33] with the wave resource peak often following that of the wind.

3) Increase the TRL: TRL progression is essential to advance an initial idea to a fully developed and

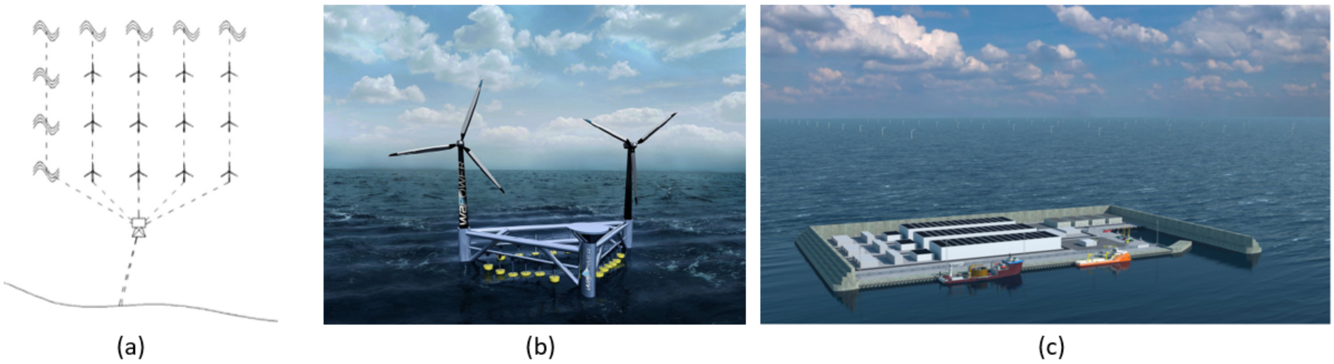

Fig. 3. Wave and Wind technology combinations: (a) A co-located array with a perimeter of WECs [4]; (b) A hybrid device, W2Power by Pelagic Power [30]; (c) An artistic impression of an energy island [6].

commercial entity. Concepts also need to cross the ”valley of death” that occurs from TRL 4-7, where a project often needs to move from public funding to securing private investment. Funding requirements also increase due to the need to scale up to achieve economies of scale. As FBOW dominates the MRE market, it is extremely difficult to obtain the necessary investment and concepts must demonstrate real excellence and innovation to stand a chance and influence original equipment manufacturers (OEMs).

To maximise this opportunity, hybrid devices and co-located projects must take full advantage of new numerical modelling methods that can drive development. Improved tank testing can help enable more devices to be tested in larger facilities. Such test facilities could test WECs that act as wave shielding in a co-located arrangement and also analyse the behaviour of hybrid systems. Crucial in-tank testing and numerical validation can help prove technologies and accelerate development. Combined floating wind and wave devices should use this method of high quality testing to test full-scale prototypes before applying for funding for full-scale demonstration systems.

C. Critical points (disadvantages)

There are some disadvantages of combining the two technologies that may prevent its early deployment, such as: (i) Different times of development: As far as wind technology is concerned, it is based on the well-known (and validated) onshore wind turbines. The difference is that the foundation is now floating and the expected loads can be different. Regarding the WECs, it is still a system for which there are not yet many prototypes that have been tested and validated at full- scale in real sea conditions. The combination of the two systems can increase the perception of risk of failure. This means that it is more difficult to obtain investment and funding for these types of projects and that insurance costs are higher; (ii) Marine spatial planning: When selecting the location to deploy these systems one was to perform a multi-objective optimization where not only criteria like bathymetry, seabed geology, and environmental restrictions, but also a location where there is maximum production of wind and wave power [34]. This could be difficult to achieve and could cause a decision between maximizing one or another [35]; (iii) Survivability: The open ocean is an extremely difficult environment in which to maintain these devices. While there is some experience with near-shore deployments, the offshore environment poses a major challenge as strong winds, waves and tides have to be taken into account in the design phase of the equipment.

D. Markets

The market integration of offshore wind and wave energy is a challenge. Apart from the fact that some prototypes of the systems described in Sec. III-A are currently being tested, it is not plausible that the energy generated is competitive compared to the current prices of other resources (e.g.: solar and onshore wind) [36] at this stage. The new paradigm created by the energy transition requires a new generation mix with almost 100% of renewable energy sources. Yet there is no single solution for every region of the world when it comes to energy supply. Not every country has the resources or the land area to deploy such technology. Many countries are now looking to the ocean again to explore its possibilities and space. In addition, there are non-energy markets where there is an opportunity for faster development of offshore wind and wave technologies [37].

Making the use of good marine spatial planning exercise, there are some markets that can flourish or be created with combined wind and wave energy technology. These include i) isolated power systems, ii) water desalination, iii) offshore data centres, iv) hydrogen production and v) low-carbon vessel refuelling. The use of generated energy for all these markets can be controversial in that it could be argued that there are other technologies using other resources that are now more mature and can offer a much lower price (they are in direct competition). Some niche markets, limited to those for which the only plausible solution is a combined wind-wave technology (far from shore), are for example: (i) Isolated power systems; (ii) Aquaculture of fish and algae; (iii) Shipping industry; (iv) Exploitation/exploration of marine resources; and (v) Offshore oil and gas industry, among others.

IV. Decarbonization potential

It is common knowledge that burning fossil fuels to generate electricity releases carbon into the atmosphere and contributes to global warming. For ease of comparison and consistency, the main gases contributing to global warming, namely carbon dioxide, methane and nitrous oxide, are summarised in mass of carbon dioxide equivalent per kWh [38]. In the present study, it is used: g CO2eq/kWh.

Of the fossil fuel power plants, coal-fired generators are one of the largest contributors at 675-1689 g CO2eq/kWh [39]. Combined cycle gas turbine (CCGT) power plants account for 365-488 g CO2eq/kWh [40]. This is significantly less than coal, but still significant as gas will continue to be a part of the energy system in the future, especially if it is to serve as a grid backup due to its fast response times. Nuclear energy is in a grey area between fossil fuels and renewables, mainly because of the environmental problems caused by spent nuclear fuel. The carbon dioxide emissions of nuclear energy have been calculated to be 9-110 g CO2eq/kWh, with a median of 13 g CO2eq/kWh [41].

Renewable energy sources do not release emissions when generating energy. Nevertheless, there are negative climate impacts associated with the project phases: especially during construction, logistics, O&M and decommissioning. Also to be considered is the embodied carbon of the materials, which are often largely steel and concrete [39]. The current emissions generated by renewables are far lower than those of most fossil fuel power generators, but they are still significant and there are pathways to further reductions. The carbon intensity of renewable energy generators was studied by [42] and found to be highly variable between and within renewable generation methods, with limited data available for wave and tidal power in particular. Wave energy was found to emit 25-50 g CO2eq/kWh over its life cycle [43]. A study of the Pelamis wave power plant found 22.8 g CO2eq/kWhwith conservative assumptions [44]. This study attributed 42% of carbon emissions to materials used in construction, transportation associated with the supply chain, and installation and O&M. The study finds that these areas are most important for reducing emissions through efficient materials and greener transport methods.

The life cycle emissions of offshore wind turbines were calculated to be 13.0±5.2 g CO2eq/kWh, with a range of 5.3-24.0 g CO2eq/kWh [45]. Offshore wind turbines have lower carbon emissions than onshore wind turbines, mainly due to economies of scale from larger turbines and higher capacity factors. In comparison, emissions are higher during the construction phase due to greater land degradation and loss of forests, as well as large vessel requirements. FOW and wave energy should target economies of scale to both reduce carbon emissions and improve LCoE. To further reduce emissions, care should be taken to minimise impacts on forests and other forms of carbon sinks, especially during the construction phase and when selecting the optimal location for the export cable. Alternatives to long-distance transport should be chosen, possibly by selecting local manufacturers, but this may have a negative impact on costs. Some of the main decarbonization methods, grouped according to the five main life cycle stages of an MRE project [46] are listed in the following sub-sections.

A. Development and Consenting (D&C)

This includes initial project front end engineering, surveys, metocean assessment and environmental impact assessments: (i) Site selection - As both technologies use similar mooring systems, a joint operation could carry out site surveys for both technologies. This would reduce the number of vessels needed and save both emissions and project costs; (ii) Site optimisation - By harvesting energy from the wind, FOWTs create a downstream wake that increases turbulent flow and reduces the amount of energy that can be harvested from downstream turbines. Turbines need to be appropriately spaced to minimise the wake effect of the upwind turbines on the downwind turbines while ensuring efficient use of the site, typically seven rotor diameters apart [47]. A co-located arrangement would further optimise site space, as the height of the WECs would not interfere with the hub height of the wind turbines. Distributing WECs between FOWTs would maximise site space and energy production. In addition, the installation, O&M and decommissioning phases could take place in a smaller area, which would reduce life-cycle emissions and shorten transport time for vessels. With evenly distributed co-located arrays, the WECs could also be connected to the existing FOW array cable network. This would make better use of capacity without requiring additional cables just for the wave energy devices. This is not the case for non-uniform arrays, where the wave transducers are placed to make best use of the wave energy and are not located between the FOWTs. This would also not be the case for WECs located in a wave shield perimeter, where additional array cables are required to transmit power to a common substation.

B. Production and Acquisition (P&A)

Cumulative emissions of a wind turbine are depicted in Ref. [48]. It is seen that P&A constitute around 91% of total project emissions, through 84% in the manufacturing phase and 7% through transport. It is in this project phase where most of the most significant carbon reduction impacts can be made: (i) Platform materials - MREs are usually made of steel, cast iron and concrete, which require extensive heat, energy and is very carbon intensive. Reducing the wave loading could reduce the platform size and thus the weight and material content of the platform. Energy-intensive materials are predominantly used for a FOWT, with reinforced concrete accounting for about 60% of the total material consumption, steel 30%, cast iron 6% and copper 2%. More environmentally friendly methods of steel and concrete production, perhaps using hydrogen, could be a way to reduce emissions in this area in the future, but such methods could involve higher project costs. The use of recycled materials should also be strongly considered in the selection of materials. In Ref. [38] it was found that when recycled steel was used, the carbon budget could be reduced by about 50%, from 4.59 GWh to 2.28 GWh of primary energy for a 2 MW FOWT. The production of cast iron is about five times higher than the initial production due to the additional emissions caused by mining, processing and transport. A 2MW wind turbine would require 0.81 GWh of primary energy for original production, compared to 0.16 GWh for recycled cast iron. There are also opportunities for the use of green energy sources in the production process, with green hydrogen providing a low-carbon solution for ammonia production, which is an essential part of cast iron production. When using primary copper, the raw materials need to be concentrated and energy-intensive processes such as electrolysis and smelting are required to achieve purity. The production of a 2 MW turbine consumes 47.3 MWh of primary energy. Secondary copper would save 61.3% of the energy demand, with a primary energy consumption of 18.3 MWh. Compared to the full use of recycled materials, which results in a total carbon consumption of 9.78g CO2eq/kWh, the carbon content without recycling and with original materials increases by 78% and the payback time of the wind turbine by 0.65-1.15 years; (ii) The power generation mix in the country of manufacture is also extremely important and should be considered in the selection process. In Ref. [48] it was found that the same manufacturing process in Germany costs only half as much carbon as one carried out in China. This is mainly due to the higher share of coal in power generation in China; (iii) Shipping and logistics - The contribution of transport to total greenhouse gas emissions can vary, with Ref. [48] defining a range of 0.2-28.3% and an average of 11.8%. This is still significant and can be mitigated by closer geographic selection of Original Equipment Manufacturers (OEMs) and creating a localised supply chain wherever possible.

C. Installation and Commissioning (I&C)

This includes all operations that use the components of the hybrid farm, including cable laying, assembly and wet towing of the equipment, and connection on site. Installation of both WECs and FOWTs can be assembled in port and towed to the site by the same vessels, often tugs. The need for heavy lift vessels can result in prolonged periods of waiting for weather windows to allow work to be carried out at sea, which can increase project costs and fuel consumption for unused vessels. Wet towing of WECs and FOWTs for on-site positioning often requires only vessels that are readily available in most ports, and operations can be more flexible than BFOW. When installing a co-located array consisting of perimeter WEC wave shields, they could be installed first to create a protective lagoon that could increase the weather window for installation of the FOW equipment. This would shorten the times for the vessels at sea and reduce fuel consumption for the installation vessels.

D. Operations and Maintenance (O&M)

Defines the processes required to keep the hybrid farm operational, including inspections, preventive repairs and conditional repairs. As with I&C, O&M costs and fuel consumption increase with distance from the coast, making site selection extremely important: (i) Shared vessels, technicians could inspect WECs and FOWTs together. If they are hybrid, fewer units need to be inspected and thus less fossil fuel is used for transport. O&M remains very carbon intensive. WECs acting as wave guards could also reduce the need for repairs and improve access conditions for site visits; (ii) Wave shields - Adopting a perimeter of WECs in a co-located farm would increase the energy absorption of the prevailing wave height, thus increasing the energy production of the park while decreasing the energy in the artificial lagoon. Ref. [49] defines a cutoff wave height of about 1.5 m, with wave climates exceeding this value preventing safe access for maintenance vessels. This delays O&M activities, which can reduce equipment availability. The use of wave shields provides the same benefits as shared operations (shared cables, moorings, vessels, etc) while helping to reduce significant wave heights in the lagoon. The study found that accessibility increased in all cases, by up to 82%. This can be seen in Ref. [49], where the initial wave heights were reduced from about 3 m to about 1.0-2.5 m within the lagoon, which was achieved by the extent of the wave shields. Increasing the number of rows also has a positive effect on reducing wave heights. This could help maintain longer weather windows with safe access for service vessels, which would increase the capacity factor and availability of the hybrid farm, increase energy production and reduce the corresponding carbon dioxide emissions per kWh.

E. Decommissioning and Disposal (D&D)

As with installation and maintenance works, a lagoon environment created by a perimeter of WECs would increase the weather window for decommissioning works.

High-quality materials can also extend the life of the project. Ensuring a high proportion of recyclable materials in the project can result in fewer original materials being used in future projects, which, as discussed in Ref. [38], can reduce project emissions by around 50% in some cases.

F. Moorings

There is a potential for shared moorings between devices, however this would increase the complexity of the system and could unbalance the FOWTs. Reduced thickness of mooring lines might be required for FOWTs if there is an outer limit of WECs, as a lower wave energy environment might allow thinner lines and less material for mooring systems.

G. Electrical infrastructure

There is great potential for cost savings and materials here. Depending on the layout of the farm, array cables, substation and export cables could be shared. When comparing a shared electrical system to two separate farms, each requiring a substation and export cables, there is great potential for cost savings and materials savings from a co-located array or hybrid equipment. Depending on the design of the farm, the array cables, substation and export cables could be shared, with higher capacity factors resulting in high cable usage factors due to a combination of staggered wind and wave generation profiles. Shared cabling would result in fewer cable laying vessels, fewer O&M inspections and fewer repairs. To maintain high conductivity and reduce electrical losses, array and export cables require large quantities of high quality metals such as aluminium and copper. As shown in Ref. [50], capital costs (which depend almost entirely on material consumption) can be reduced by an average of 10% for hybrid wind and wave farms.

H. Staggered electrical production

A recurring problem with renewable energy is the intermittency of supply. Currently, wind generators in a system will inject power at the same time, which does not necessarily coincide with demand. This phenomenon can lead to the need for additional backup power plants, which are often fossil fuel based, as they need to ramp up and down quickly, especially for CCGT plants. In Ref. [51] these backup generation requirements are documented in detail. Balancing errors in the day-ahead price market combined with the intermittency and short-term unreliability of renewable energy power plants require operating reserves that can respond in seconds. Weak grids may need to be significantly rebuilt to handle the large peaks of a grid that is even more dominated by offshore wind. Grid infrastructure is extremely expensive, highly regulated and is also very carbon intensive. There are also problems with the adequacy of the electricity grid, with fossil-fuelled back-up power plants constantly running at low capacity in case they are needed to meet peak demand.

A hybrid wind-wave system first generates power through FOWTs by the initial faster wind resource. Then the waves generated by the same weather system arrive and are extracted by the WECs. In this way, a weather system can generate electricity over a longer period of time. This increases the chance that renewables will be able to meet demand. It also increases the reliability, stability, and predictability of the system, so fewer conventional gas turbines and other equipment need to be used or kept running, which reduces emissions in the power system. This was confirmed by Ref. [50], which created hybrid WEC-FOWT scenarios at two well-known offshore wind farms - Horns Rev in Denmark and Alpha Ventus in Germany. At Alpha Ventus, power output variability was found to decrease by up to 6% compared to existing stand-alone systems. Downtime was also reduced by up to 76% and the capacity factor increased by 6% for a mixed system of 50%. For Horns Rev, downtime decreased by up to 87% and the capacity factor increased by 3% for a mixed wind farm with 10% WEC.

I. Economies of Scale

Larger offshore devices allow for fewer site visits, lower installation frequency and higher capacity factors. There are also fewer cable connections, as fewer array cables connect fewer turbines. Higher capacity cables can also provide excess capacity to WECs without overloading them. Larger turbines and WECs also require fewer logistics vehicles for transport and less time for installation. Increasing the size of the equipment would reduce the amount of materials per MW of generation, as the weight of materials does not increase linearly with power output.

J. Project lifetime extension

Another additional benefit of a perimeter of WECs in a co-located array, as described and studied by Ref. [49] would be the reduction of hydrodynamic forces acting on the floating platforms and mooring systems, as well as forces acting on the nacelle, including accelerations caused by the movement of the platforms. Reducing these forces would reduce structural fatigue, tower bending, rotor blade degradation and mooring line stress - all factors that could contribute to shortening the overall life of the project when the decommissioning phase begins. Extending the life of the project could help delay the decommissioning phase and allow a power plant to continue generating electricity. This would also help to delay the carbon-intensive manufacturing phase of a new project.

V. Case study: Portugal and impact in the decarbonization

This section aims to determine the impact of multi-use platforms in Portugal and how they would affect Portugal's decarbonization roadmap [52]. This is not about small applications where the power requirement is less than a few kW, but a case study in the utility sector. It is used as reference the numerical simulations of a wind-wave platform deployed in Porto de Leixões, Portugal [18]. This location may be assumed as representative of the wave climate of the Atlantic Ocean [53].

A schematic representation of the wind-wave platform used for this case study is showed in Fig. 4. This platform is composed by a 5 MW wind turbine and four OWC WEC's with a rated power of 1800 kW, used as foundation for the wind turbine. The wave and wind climate characterisation in Porto de Leixões was used to assess the wind and wave power production of the platform (see red circle in Fig. 4 (b)).

Table I presents the results from the numerical simulation of the device described above and showed in Fig. 4. As it can be seen from Tab. I, for this platform design, the wave power production may represent around 25% of the wind turbine power.

In Ref. [52] the government's scenario for the energy mix in 2050, called *Mitigação -75%*, is shown. Where there is a reduction in greenhouse gas emissions of up to 75% and the share of renewable energy sources is limited to available resources. This assumes that offshore wind farms are deployed in the area shown in Fig. 4 (b) in a black dashed rectangle [52]. The scenario

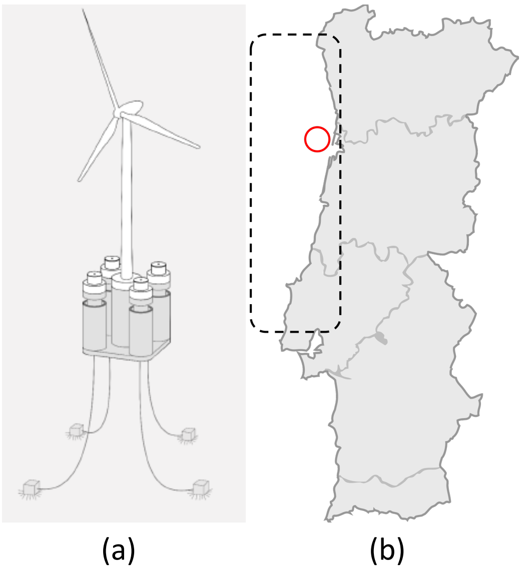

Fig. 4. (a) Combined wind-wave platform considered for the case study. Reproduced from [18], (b) Deployment location: Red circle - Porto de Leixões, case study [18]; Black dashed line rectangle - Area considered for the estimations in [52].

predictes that in 2050 offshore wind technologies will represent a total produced energy of $E_{\mathrm{OW}}^{2050} = 8.6\,\mathrm{TWh}$. Assuming that these farms are a wind-wave platform similar to the one described in Ref. [18], the total energy produced would be $E_{\mathrm{WW}}^{2050} = E_{\mathrm{OW}}^{2050} \times 1.25 = 10.8\,\mathrm{TWh}$. This corresponds to an increase in produced energy of $\Delta E = 2.2\,\mathrm{TWh}$ and a 3% share of the Portuguese energy mix in 2050 of wave energy. Estimations in Ref. [52] shows that in 2050 the total produced energy from natural gas is $E_{\mathrm{G}}^{2050} = 2.1\,\mathrm{TWh}$, this technology emits, in average, $\mathrm{GHG}_{\mathrm{G}} = 427\,\mathrm{g\,CO2eq/kWh}$ [40]. The produced green house gases emissions for the case of the wind-wave technology is $\mathrm{GHG}_{\mathrm{WW}} = 36\,\mathrm{g\,CO2eq/kWh}$, see Sec. IV. So, if the share of natural gas was to be replaced by the energy produced by the wind-wave device proposed, the impact in the decarbonization would then be a reduction in GHG emissions of $R = (\mathrm{GHG}_{\mathrm{G}} - \mathrm{GHG}_{\mathrm{WW}}) \times E_{\mathrm{G}}^{2050} = 821\,\mathrm{kton}$.

VI. Conclusions

The globally imposed rules to mitigate climate change require a new generational mix across the globe. In addition, with the growth of the so-called blue economy, there are opportunities for the development and deployment of renewable offshore energy. To take advantage of these opportunities and succeed, it is necessary to think outside the box, from the design to the disposal of these devices, and understand where value creation meets the needs of maritime economic actors. Floating wind and wave power systems are still in relative infancy. As far as wind turbines are concerned, they face strong competition from bottom-mounted offshore wind turbines and new challenges. Nevertheless, the increase in energy generated at the same rated power is tempting. A large number of wave energy devices have already been tested at sea, but the results may indicate that further developments are needed to bring the technology to market.

The combination of wind and wave energy systems is possible and promising. Combining the two technologies would increase TRL, reduce risk for both sectors and lower prices. A greater number of benefits arise from this coupling, namely cost sharing, increased energy production and huge decarbonization potential. Some prototypes of different types of this combination of technologies are being developed in current European projects and some of them are being prepared for deployment. These technologies are suitable for a large number of markets where the only option for energy production is either renewable ocean energy or fossil fuels (mostly diesel and natural gas). As they are the most sought-after energy resource in some markets, they can act as a stepping stone to bring costs down to a level where offshore energy technologies can become competitive for the provision of grid power.

Numerical simulations for a 6.8 MW wind-wave platform were used to determine the impact on decarbonization in Portugal using generation mix estimates in 2050. It was found that the use of a wind wave platform instead of a single floating offshore wind turbine would result in a 25% increase in generated energy. Furthermore, using this additional energy package and removing natural gas from the generation mix would lead to a remarkable reduction in greenhouse gas emissions of 821 kton.

TABLE I
Case study - Rated power and produced power for Porto de Leixões wave/wind climate, see Fig. 4 (b).

	Rated power (kW)	Produced power (kW)
Wind	5000	2400
Wave	1800	600
Combined	**6800**	**3000**

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