Opportunities for cross-fertilisation between the shipbuilding industry and the emergent offshore wind energy sector in Colombia: an overview of floating platformtechnologies

Oportunidades de fertilización cruzada entre la industria de construcción naval y el sector emergente de energía eólica offshore en Colombia: una visión general de las tecnologías de plataforma flotante

Oportunidades de fertilização cruzada entre a indústria de construção naval e o setor de energia eólica emergente offshore na Colombia: um panorama das tecnologias de plataforma flutuante

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Abstract

Introduction: This paper provides a review and analysis of cross-fertilisation opportunities between the shipbuilding industry in Colombia and the Offshore Wind Energy (OWE) sector.

Problem: In Colombia, offshore wind resources are available, so it is necessary to analyse the potential areas where national shipbuilding industries could take advantage of their knowledge and experience for the development of OWE projects.

Objective: The study is aimed at identifying the main aspects involved in the design and construction of floating platforms for Offshore Wind Turbines (OWTs) and to examine the restrictions and capabilities of the Colombian shipbuilding industry for their implementation.

Methodology: A review of the technical aspects related to Floating Offshore Wind Turbines (FOWTs) and the integration of shipyards with the OWE value chain was carried out; subsequently, cross-fertilisation opportunities between the shipbuilding industry in Colombia and the OWE sector were analysed and discussed.

Results: There are multiple areas in which the shipbuilding industry in Colombia could participate in the value chain of the floating offshore wind energy sector in Colombia, taking advantage of the knowledge and experience in topics such as shipbuilding, marine engineering, steelmaking, and construction techniques.

Conclusion: The Colombian shipbuilding industry could enter new R&D areas derived from OWE projects, while its most significant contribution would be its experience for the design and construction of vessels for the installation, operation and maintenance of FOWTs.

Originality: Through this investigation, the correlation between the Colombian shipbuilding industry and the emerging OWE market is identified.

Limitations: At an international level, FOWTs are under development and testing. In the national context, currently, there is not an established OWE sector.

Keywords: Floating Offshore Wind Turbines; Offshore Wind Energy; shipbuilding; shipyard capabilities.

Resumen

Resumo

1. INTRODUCTION

Nowadays, the Offshore Wind Energy (OWE) sector is experiencing increasingly rapid progress in the international arena. Among currently available large-scale solutions to harvest energy from renewable sources, the Offshore Wind Turbines (OWTs) have responded to some of the challenges faced by earthbound applications, such as the land limitations for new deployments and the congestion of electrical transmission lines [1].

As OWT technology develops, it continues its transition to deeper waters where the conventional fixed-bottom foundations are not technically and economically feasible [2], [3]. This transition is enabled by the use of floating platforms, designed and constructed to provide a safe and reliable foundation for OWTs to be installed far away from the coast. Several types of floating structures have been presented in previous studies [4]–[7], primarily four concepts: barge, semi-submersible, spar-buoy, and Tension-Leg Platform (TLP). Despite their technical differences, a common feature between these floating platforms is that traditional shipbuilding skills can be employed for their manufacturing process [8], [9, p. 6]. Consequently, there is a rising number of shipbuilding and maritime-related companies worldwide who are using their existing knowledge to participate in the value chain of the OWE sector.

In a local context, although wind energy generation is not yet widespread Colombia, some previous reports indicate that there are available onshore and off-shore wind resources along its Caribbean Sea coast, with promising potential near to La Guajira region [10], [11]. The Colombian government has also started to promote the implementation of non-conventional energy sources through specific legislation (e.g. Law 1715 of 2014) and the awarding of five wind energy generation projects during the last energy market auction held in 2019 [12]. Therefore, it is necessary to explore possibilities to take advantage of the offshore wind resources, starting with the design and adaptation of existing technology to Colombian conditions, to form an emergent Offshore Wind Energy Sector in this country.

Having this perspective in mind, the authors analyse the prospective areas where the national shipbuilding and maritime-related industries can leverage their knowledge and experience for the development of OWE projects involving floating platforms in Colombia. For this purpose, this paper presents an initial review of technical aspects related to Floating Offshore Wind Turbines (FOWTs). Then, some case studies are summarised to exemplify the integration of shipyards to the value chain of the OWE. Finally, the opportunities for cross-fertilisation between the shipbuilding industry in Colombia and the OWE sector are discussed.

2. REVIEW OF FLOATING OFFSHORE WIND TURBINES (FOWTs)

The concept of OWE generation is not new. As argued by Musial and Ram [13] and Manwell et al. [14, p. 461], initial ideas go back to the decade of 1930 with Hermann Honnef"s drafts for a direct-driven offshore wind installation. Later, in the decade of

1970s, additional studies were carried out by William Heronemus at the University of Massachusetts. He proposed the "windship" multi-rotor wind turbine, which was an array of conventional turbines on a common frame intended to float on a large buoy [15]. Although Heronemus" OWTs were never built, his vision set up the foundations for modern offshore wind farms.

The implementation of the first large-scale projects of OWE started in 1990 in Europe, specifically in the waters of the North Sea [16]. Nowadays, some studies show the global cumulative installed capacity of OWE is within the range of 20 GW and 25 GW [1], [2, p. 25], [17, p. 7]. In contrast, approximately 90% of this capacity is located in the area of the North Sea [1, p. 42]. There are expectations of significant growth in the number of deployments for the upcoming years in North America and Asia.

Fig. 1. Conceptual design of the "windship"
Source: W. Heronemus [18]

There is a widespread agreement that one of the main drivers for the offshore wind industry is the requirement of accessing new areas with higher wind potentials [3]. These can be found further from the coast [19, p. 71], where water depths are usually greater than the limits for economically-feasible projects using the conventional fixed-bottom technologies [2, p. 33]. For this reason, in recent years there has been an increased interest in the design and development of floating systems for OWTs aimed to operate in deep waters (more than 60 m). Consequently, OWT technology is transitioning towards floating applications, following a path as depicted in Fig. 2. Indeed, Floating Offshore Wind Turbines (FOWTs) offer some relative advantages over the fixed-bottom technologies:

They provide flexibility to reach remote places with stronger and more constant winds, which translates into a higher energy generation [14], [20].

- Their installation is less-invasive to the seabed [21].
- Since their operation is undertaken far away from the shore, the visual and noise impact of the wind turbines to people is reduced [20].
- The possibility to install them in the open ocean, regardless of the water depth and seabed conditions, enables vast spaces to sit large-scale projects [14], [22].
- They have the potential for mass production and wide-ranging wind turbine innovation [16].
- FOWTs can be assembled along the coastline and then carried to their final location. Hence, their sizes are not constraint by the available resources for land transportation [20].

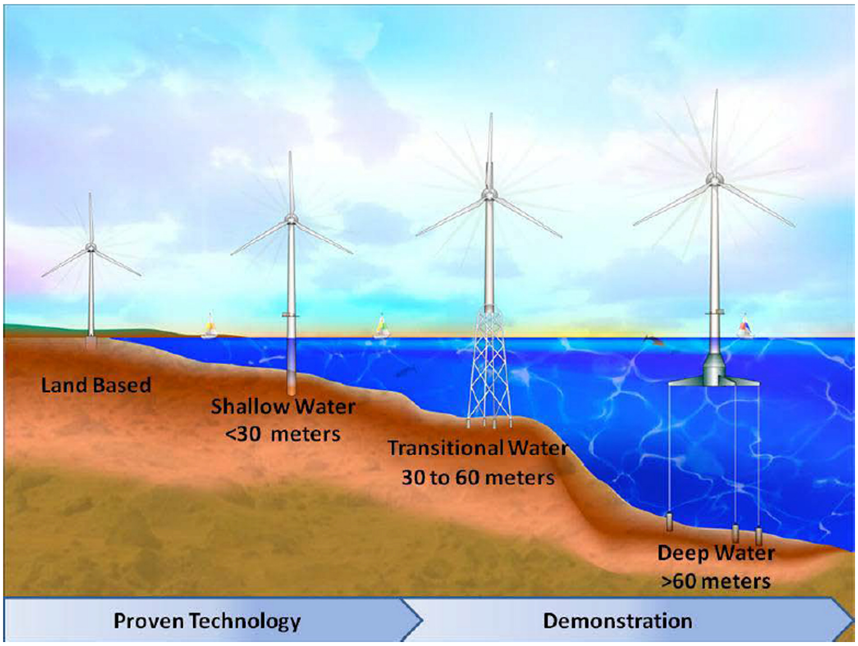


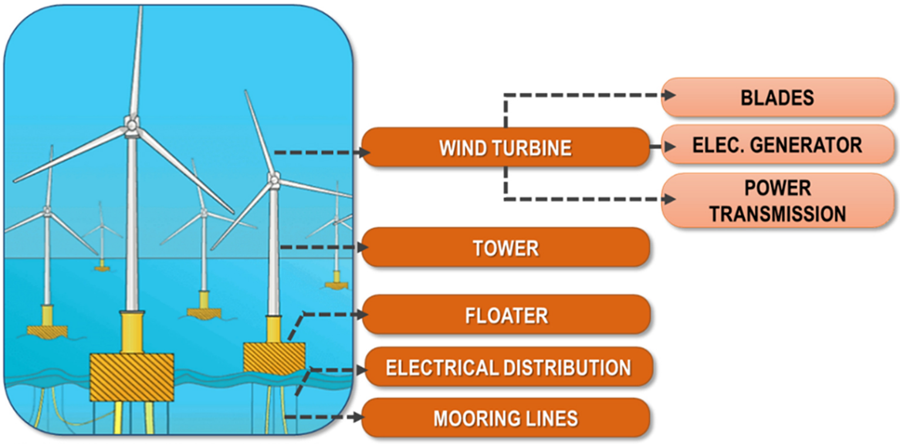
Fig. 2. Transition from onshore wind energy generation to FOWTs

Source: [13, p. 5].

2.1. Basics of Floating Foundations for FOWTs

Although the technological solutions for FOWTs are diverse, previous studies have described their configurations in terms of principal components, which are common to all of them. Barter [23, p. 10] suggests a “building block” approach, presenting a partial list of ten primary elements that form a wind energy system, namely turbine, platform, mooring, anchors, tower, drivetrain, assembly, electrical components, operation and maintenance, and plant. On the other hand, Kang et al. [24] made a system decomposition for a Failure Modes and Effects Analysis (FMEA), identifying 49 elements which were grouped into the following categories: Blade system; generator, electrical and electronic components; transmission system; support system, and auxiliary system. Moreover, Tong [22] and Serrano Morán [25] outline design considerations for three main blocks: the floating structure, the mooring system, and the wind turbine itself.

Based on the literature findings, the authors propose a System Breakdown Structure (SBS) for OWTs, as shown in Fig. 3. Given the relevance of the floater and the mooring lines for FOWTs, a short technical overview of these parts will be provided hereinafter.



https://w3.windfair.net/uploads/notice/preview/32604/carbon_trust_20190912.png

Fig. 3. SBS of a floating offshore wind turbine (Source: Authors” diagram based on Tong **Source:** [22] and Barter [23])

2.1.1. *Main types of floaters and mooring lines for FOWTs*

A FOWT structure is subjected to dynamic forces due to the action of the waves and the wind. These forces cause movements, as represented in Fig. 4. Therefore, the floater must be dimensioned to satisfy the following requirements [26]:

- Provide enough buoyancy to support the combined weight of its structure and the wind turbine.
- Remain in an upright position for all design wind and wave conditions. In other words, the floating platform should restrain pitch, roll, and heave motions within acceptable limits [4], which are usually set by specific standards.
- Prevent excessive loading on the wind turbine due to dynamic forces acting on the floater.

Must be economically feasible.

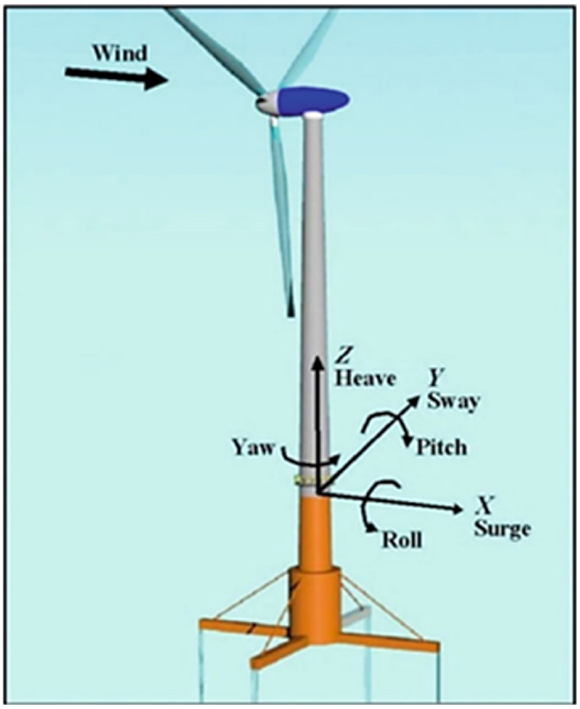


Fig. 4. Degrees of freedom in a FOWT
Source: [26], [27]

Fig. 5 illustrates the most common floating structure solutions for OWTs: barge, semi-submersible, spar-buoy, and tension leg platform (TLP). Each of these types of structure will be briefly discussed below.

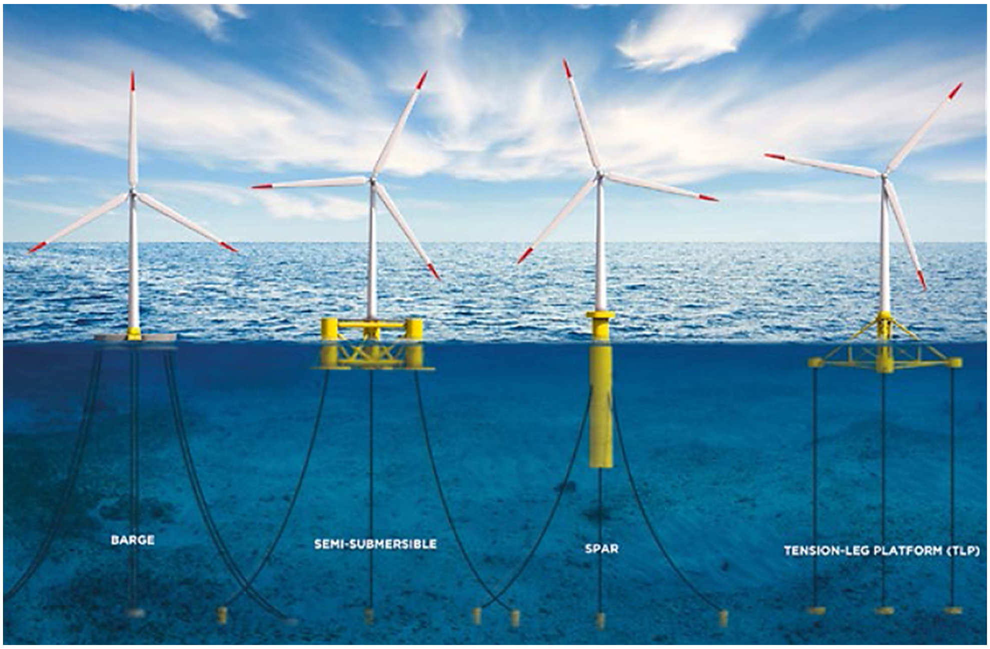


Fig. 5. Types of floating platforms for OWTs
Source: [3]

a. Barge-type: Also known as "pontoon-type", it is composed by a flat-bottom box-shaped structure, which maintains its hydrostatic stability employing the concept of distributed buoyancy, through a large waterplane area and a shallow draft to obtain a righting moment [28]. For station keeping, the barge-type FOWTs can use catenary (loose) mooring systems. However, as argued by Wang et al. [7], this type of floater is more suitable for calm waters since they are prone to experience large roll and pitch motions.

b. Semi-submersible type: Sometimes referred to as "column-stabilised", comprises a set of large columns connected through smaller tubular members or pontoons [7]. As its name indicates, each column is partially submerged, which provides additional waterplane area for stability. Moreover, ballast weight can be applied to the columns to contribute to the hydrostatic stability while the interconnecting structures provide extra buoyancy [21]. Similar to the barge-type, to avoid the platform from drifting, it can be moored by catenary or taut lines, attached to each column [21], [28].

c. Spar-buoy-type: This type of structure is formed by the floater, which is a central buoyancy cylindrical tank, and ballast weights for its stabilisation [4], [21]. The spar-buoy requires a large draft to minimise the heave motion, hence it is necessary to have deep waters for its deployment [7]. For station keeping, the spar-buoys can use either catenary (loose) or taut mooring systems with anchors, as shown in Fig. 5.

d. TLP-type: Consists of a cylindrical central platform with three legs attached to the main body. Like the semi-submersible type, the TLP-type has part of its structure below the waterline, although the latter is more buoyant than the former [29]. For this reason, TLPs employ vertical mooring lines, called tendons or tethers, extending from their legs to the seabed where they are anchored [7]. The tethers are intended to maintain the stiffness of the mooring system while they provide a righting moment for stability purposes [30].

According to literature findings, three classification approaches can be followed for FOTWs: By their stabilisation method, by their means for station keeping, and by the number of OWTs in a single platform, as summarised in Table 1.

Table 1. Classification of FOWTs as per literature findings

Classification	**Type of floating structure**			
	Barge (Pontoon)	**Semi-submersible**	**Spar-buoy**	**Tension-leg platform (TLP)**
By stabilisation method [4], [31], [32]	Buoyancy-stabilized	Hybrid (ballast + buoyancy-stabilized)	Ballast-stabilized	Mooring line-stabilized
By station keeping method [27], [33]	Catenary loose mooring	Catenary loose mooring	Catenary loose mooring	Vertical (tensioned) mooring
By number of OWT [27]	Single-turbine	Single-turbine	Single-turbine	Single-turbine
	Multiple-turbine	Multiple-turbine	Multiple-turbine	Multiple-turbine

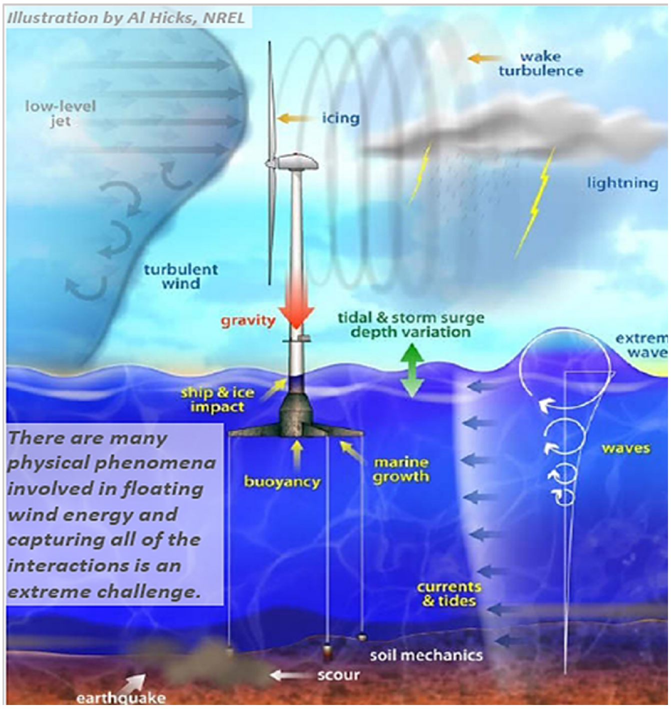
Source: Compiled by the authors from the cited references.

2.2. Design and engineering challenges for FOWTs

FOWTs are considered to be complex systems [31] due to the strong interactions of the platform with a variety of environmental factors such as wind turbulence, waves, currents and tides, lightning, seabed soil mechanics, among many others (Fig. 6). The FOWT types, presented in the previous section, address the effects of these physical phenomena through different technical strategies in order to achieve three primary goals [22, p. 403]:

- Minimising the overall size, thus, the cost.
- Maximising stability.
- Minimising dynamic motion response up to permissible levels for the correct operation of the wind turbine and its auxiliary systems.

As stressed by Butterfield et al. [4], there is not a perfect type of FOWT. Hence, during the design process, it is necessary to undertake some trade-offs to reach a balanced solution, considering that each type of FOWT has its advantages and disadvantages, which are presented in detail in IRENA [21, p. 5]. As a result, the design process requires a systems-focused approach [23], where Multi-Disciplinary Analysis and Optimisation (MDAO) techniques can be employed to select an optimal alternative, i.e. the best functionality at the lowest possible cost, from multiple design configurations generated from the combination of the FOWT building blocks.



There are many physical phenomena involved in floating wind energy and capturing all of the interactions is an extreme challenge.

Fig. 6. Interactions of a FOWT with the environment.
Source: [23].

The design of FOWT structures poses some challenges, including:

- FOWTs are tightly-coupled systems, where both aerodynamic and hydrodynamic loads influence over all the components [23], [34]. Because of their physical nature, most of these loads (as well as their interactions) have non-linear and time-dependent behaviours. Therefore, to represent them, it is necessary to have higher-order engineering models [31]. However, designers could opt for simpler models to optimise the use of computational resources during conceptual and preliminary stages of a project.

- The initial dimensioning implies a compromise between the floatability and the minimum draught required to avoid slamming loads [31]. Slamming is an occasional event caused by waves breaking into the platform which produce severe impacts into it. These impacts translate into additional loads on the structure, reducing its lifetime due to fatigue damage [35]. A way to reduce the occurrence of slamming is by increasing the freeboard height, hence, reducing the draft. This requirement imposes a need for weight minimisation and a low centre of gravity.
- The selection of the wind turbine tends to be driven by the technological maturity of the horizontal-axis turbines used for land-based and offshore-fixed wind farms. Consequently, the use of this type of device leads to additional constrains for the floater, in terms of its maximum admissible motions and accelerations.

Regardless of the above-discussed challenges, nowadays, FOWTs have reached high Technology Readiness Levels (TLRs) [3, p. 4], demonstrating their evolution from the Research and Development (R&D) stages up to the demonstration and first product implementation. This trend can be evidenced in Musial et al. [2, pp. 35–36], who present a comprehensive list of 38 floating offshore wind projects currently in process in different locations worldwide. Some of these projects, and their corresponding type of floating platform, are exemplified in Fig. 7. It can be observed that TLP-based designs are in earlier phases of development (TLRs 6 and 7), compared with other technologies such as the semi-submersible and the spar-buoy (TLRs 8 and 9).

Experiences in the implementation of each of the projects depicted in Fig. 7 points out the importance of knowledge transfer and support among three fundamental actors: academia, government, and industry. It is possible to identify potential synergies among these actors, which could lead to the consolidation of the floating OWE sector. One of these potential synergies can be observed within the shipbuilding industries, as it will be outlined in the following section.

Fig. 7. Examples of implementation of FOWTs in different stages of development (up to TLR 8).

3. POTENTIAL SYNERGIES BETWEEN THE SHIPBUILDING INDUSTRY AND THE FLOATING OWE SECTOR: CASE STUDIES IN THE INTERNATIONAL SCENARIO

In the international context, there is a well-defined legacy from the offshore oil & gas (O&G) sector towards the OWE industry. As reported by IRENA [17], some recognised O&G platform manufacturers have successfully transitioned to the offshore wind market.

On the other hand, and due to their related technical background, ship design offices and shipyards have valuable know-how in cross-cutting areas for the FOWT projects. These include, but are not limited to, naval and marine engineering, steelwork, outfit manufacturing, and corrosion management. In other words, the design and manufacturing of FOWTs requires traditional shipyard skills in large quantities, as well as the installation, maintenance, and further decommissioning of the turbines [9, p. 6]. Hence, the different actors in the shipbuilding industry (e.g. shipyards, marine equipment manufacturers and suppliers, classification societies, marine and naval professionals) have a broad range of opportunities along the value chain of the FOWT projects, as represented in Fig. 8.

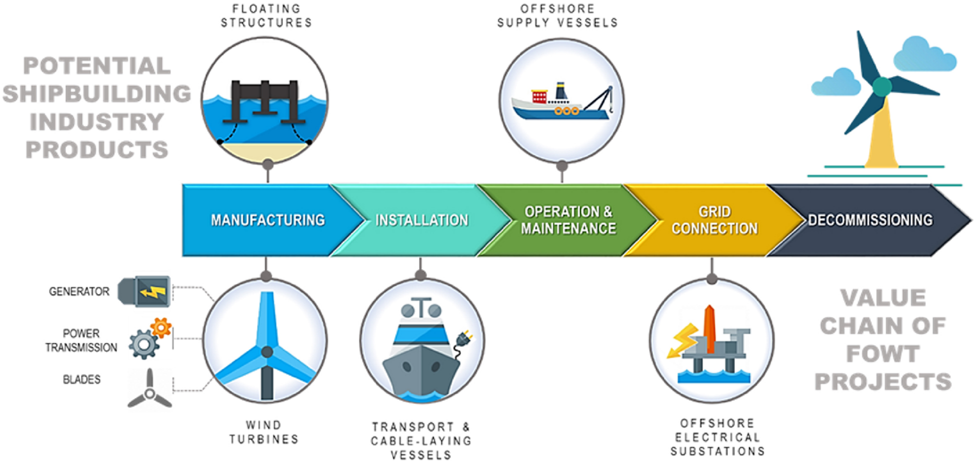


Fig. 8. Opportunities for the shipbuilding industry in the value chain of FOWT projects
Source: Authors" diagram, adapted from IRENA [17]

Table 2 presents a review of shipyards which are currently involved in the floating OWE value chain. Five major business segments of the floating OWE sector have been identified where international shipyards have started to take part, i.e. operation and maintenance vessels; design and construction of floating structures; construction of offshore electrical substations; wind turbine manufacturing / installation, and cable-laying vessels.

Table 2. Review of international shipyards with participation in the FOWT value chain

Shipyard (Country)	Business segment in the floating offshore wind value chain				
	Operation & Maintenance Vessels	Floating Structures	Electrical Substations	Wind Turbines	Cable-laying vessels
A&R (Germany)	X				
STX Europe: Chantiers de l"Atlantique (France)			X		
China Shipbuilding Industry Corporation (China)	X		X		
Crist S.A (Poland)	X				
CSBC corporation (Taiwan)		X			

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Shipyard (Country)	Business segment in the floating offshore wind value chain				
	Operation & Maintenance Vessels	**Floating Structures**	**Electrical Substations**	**Wind Turbines**	**Cable-laying vessels**
Daewoo Shipbuilding & Marine Engineering (South Korea)				X	
Damen Shipyards (Netherlands)	X				X
Fjellstrand AS (Norway)	X				
Fosen Yard Emden GmbH (Germany)		X			
Gdansk Shipyard Group (Poland)	X	X			
Havyard Group (Norway)	X				
Hyundai Heavy Industries (South Korea)				X	
LaNaval (Spain)	X				X
Lisnave (Portugal)		X			
Mars (Poland)			X		
Meyer Turku (Finland)	X				
MV Werften (Germany)	X				X
DCNS Naval Group (France)		X			
Navantia (Spain)		X	X		
Norbiskrug (Germany)			X		
Nordic Yards (Germany)			X		
Pella Sietas GmbH (Germany)	X				
Samsung Heavy Industries (South Korea)	X			X	
Technip Pori (Finland)		X			
Ulstein Verft (Norway)	X				

Source: Compiled by the authors from the shipyards" websites.

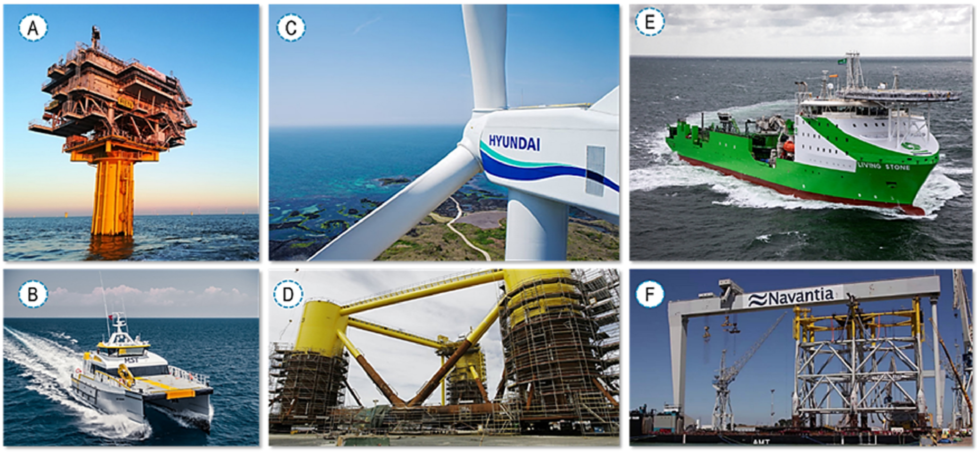
From the findings presented in Table 2, some case studies of shipyards that have introduced alternative products and services into the market, related with the value chain of offshore wind energies, are summarised below (Fig. 9):

- Damen Shipyards, in the Netherlands, has diversified its portfolio of designs to satisfy the requirements in the different lifecycle phases of an offshore wind farm. These include vessels for manufacturing, cable-laying, as well as for operation and maintenance [36].
- Navantia, in Spain, has built a strong reputation in the construction of fixed foundations for offshore wind farms, highlighting its participation in the Wikinger project (Baltic sea, Germany) since 2014 [37]. Moreover,

this company actively contributes in some of the FOWT projects currently in progress, as "Windfloat" and "Hywind", with the fabrication of two semi-submersible structures for the former and five spar-buoy type structures for the latter. Furthermore, in 2019, Navantia reported the upcoming construction of five additional floating units for the Kinkardine project, located near Aberdeen (United Kingdom) [38].

- Chantiers de l''Atlantique, part of the STX Europe group in France, has developed diverse solutions for the OWE market. However, its foremost participation is in the segment of the offshore electrical substations for wind farms, with projects such as "Westermost Rough" in the United Kingdom (2015), where they carried out the detailed design and engineering, procurement, construction and assembly, painting, and testing of the electrical substation [39]. Furthermore, in January 2020, this shipyard cut the first steel for a new electrical substation to be placed in the Saint-Nazaire offshore wind farm project in France [40].
- One of the largest South Korean shipyards, Hyundai Heavy Industries (HHI), has several references in the installation of offshore wind turbines. One of its most relevant projects is the deployment of a 5.5 MW offshore wind turbine prototype near to Jeju Island in South Korea [41]. Moreover, HHI is also involved in the development of concepts for the floating structure, as well as the integration of new turbine prototypes with other manufacturers as Doosan Heavy Industries and Construction, Hanjin Industries, and Unison [42].
- Other shipyards, like LaNaval in Spain, offer special purpose vessels for cable-laying operations [43]. An example is the multipurpose vessel "Living Stone", which is capable of undertaking cable installation between the offshore electrical substation and the diverse wind turbines in a wind farm. This ship was employed in 2018 during the cable-laying process in the installation of the Hornsea One wind farm, located off the coast of Yorkshire (United Kingdom).

A common aspect between the case studies is that most of the shipbuilders associate with other companies (not necessarily of the same industrial sector) to face the challenge of a FOWT project. Hannon et al. [5] claim that the small and medium-sized enterprises (SMEs) are increasingly taking an essential part in these associations, providing solutions in some areas where the shipbuilding industry lacks experience, such as station-keeping systems, technology design, including novel concepts of floaters and wind turbines, testing procedures for FOWTs, and installation of underwater power cables, to mention a few.



A. Offshore Electrical Substation – STX Europe (Chantiers de l'Atlantique).
Source: https://www.weamec.fr/en/blog/record_actor/atlantique-offshore-energy/

B. Operation & Maintenance Vessel – DAMEN.
Source: https://magazine.damen.com/markets/offshore-wind/damens-fcs-2710-new-and-improved-fast-crew-supplier-for-windfarm-industry/

C. Wind turbine development & installation – HHI.
Source: https://images.app.goo.gl/twAgTuvd8zfcNrPf8

D. Construction of semi-submersible floater – Navantia.
Source: https://www.elcorreogallego.es/galicia/ecg/navantia-fene-logra-liderato-mundial-eolica-flotante/idEdicion-2019-06-21/idNoticia-1189890

E. Cable-laying vessel "Living Stone" – LaNaval.
Source: https://images.app.goo.gl/jTZu2WP299ZzR7XH9

F. Construction of offshore fixed foundations for the Wikinger Project – Navantia.
Source: https://images.app.goo.gl/r5HjQzBsr8f1CdMe6

Fig. 9. Case studies: Some of the international shipyards currently participating in the FOWT value chain.

4. DISCUSSION: CROSS-FERTILISATION BETWEEN THE SHIPBUILDING INDUSTRY AND THE EMERGENT FOW ENERGY SECTOR IN THE COLOMBIAN CONTEXT

As explained in the previous section, there are many opportunities for the shipbuilding and maritime industries in the value chain of the FOW energy sector. These opportunities are underpinned by the fact that previously accumulated knowledge and industrial bases of traditional sectors of the economy are highly employed by SMEs in their transition to emergent markets, such as FOW energy [44]. Thus, it is possible to carry out a "cross-fertilisation" process where the existing knowledge, infrastructure, and methods of the shipbuilding industry can be integrated or adjusted to solve the specific requirements of the FOW energy sector, leading to diverse types of innovation. Equally, the challenges posed by the FOWT projects can stimulate either the development of new capabilities in the shipbuilding and maritime industries, or the adaptation of the existing ones to be used differently.

When it comes to the Colombian context, the regulatory framework given by Law 1715 of 2014, as well as the perspectives summarised in the National Energetic Plan 2050 (UPME, 2015) for the promotion of non-conventional energy sources, provide a motivation for the different actors participating in the national energetic system to start new initiatives for the implementation of clean technologies, such as the FOWTs. On the other hand, considering the current scientific and technological capabilities of the Colombian shipbuilding industry and the some of the R&D areas required for the potential implementation of FOW energy solutions in Colombia, the authors have identified prospects for cross-fertilisation between these two sectors. These interactions between the capabilities of the Colombian shipbuilding industry and the needs or requirements of the FOW energy sector are represented in Fig. 10, while some additional remarks about them are presented in the following sub-sections.

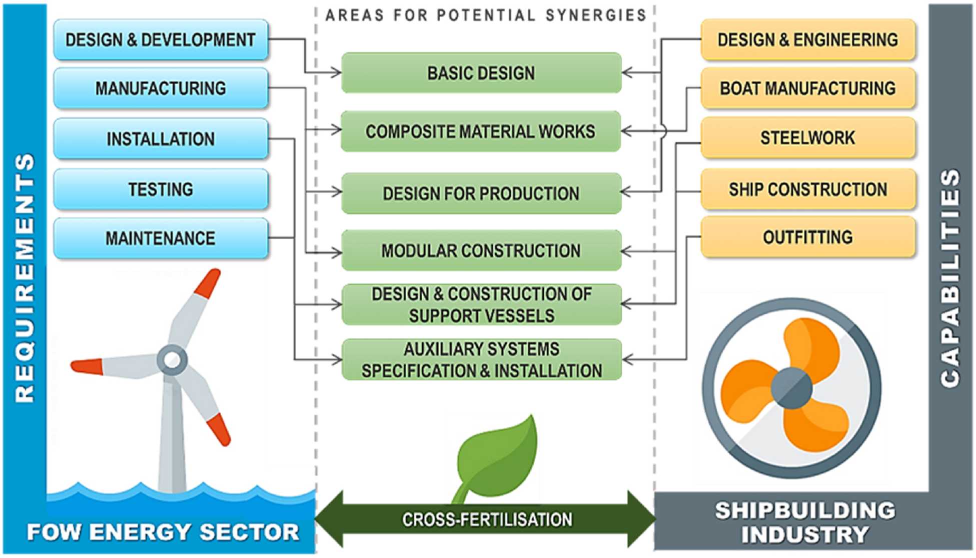


Fig. 10. Areas for cross-fertilisation between the shipbuilding industry and the FOW energy sector in Colombia

Source: own work

4.1. Design and engineering challenges for FOWTs

The Colombian shipbuilding industry has acquired some scientific and technological capabilities over the years that enable its involvement in the Research, Development, and Innovation (R&D&I) processes in the FOW energy sector. Its experience in areas such as naval architecture, design and optimisation of naval structures, and marine engineering can be harvested primarily in the basic design of the floating structure for the OWT. In contrast, at this stage, there is no foreseeable participation in the design and development stages of the wind turbine.

Regarding the design of the floater, it is worth noting that there are knowledge gaps in the use of computer tools (e.g. software for CFD and FEM analyses) to model the combined effect of wind and wave loads on the structure. Also, it will be important to consider the specific challenges depending on the type of floater (i.e. barge semi-submersible, spar-buoy, and TLP), which will imply additional design constraints in terms of buoyancy, stability, and interfaces with the mooring system.

On the other hand, due to the nature of shipbuilding projects, there is a fluent relationship between the shipyards and the classification societies, which are non-governmental organisations that establish standards for the design and construction of ships and offshore structures. This bond might facilitate the inception of new rules and regulations in the Colombian shipbuilding industry.

Finally, the association with strategic partners in the FOW energy sector will be necessary to define the following aspects, which are inputs for the design of the floating structure:

- Optimal location for the project and its environmental parameters, i.e. sea states, wind speeds and directions, water depths.
- Wind farm arrangement.
- Weights and centres of gravity of the components of the FOWT.
- Maintenance restrictions that could lead to a requirement for additional volume in the platform.
- Design of the mooring system.

4.2. Opportunities of cross-fertilisation in the FOWT manufacturing process

Colombian shipyards understand very well the engineering and construction processes for steel floating structures. They have incorporated diverse methods to prepare technical information (e.g. 3-D models, drawings, specifications, and bills of materials) for production, as well as building strategies, whose complexity increases with the size of the vessel. For instance, a modular construction approach can be applied to large ships; this means that they are sub-dividing them into smaller parts or “blocks” to enhance their producibility with regards to the available infrastructure.

Moreover, in Colombia there is a good industrial base for steelwork and outfitting production, involving processes such as metal treatment and cutting, welding, painting, block assembly, pipework, electrical foundations, manufacturing and installation, etc. Hence, this knowledge can be leveraged in the construction process of the floater and even the tower of an OWT (if metallic), although some restrictions could be found in the existing shipyard facilities to handle the massive scale of these devices.

These limitations encompass the factors described by Matha et al. [45]:

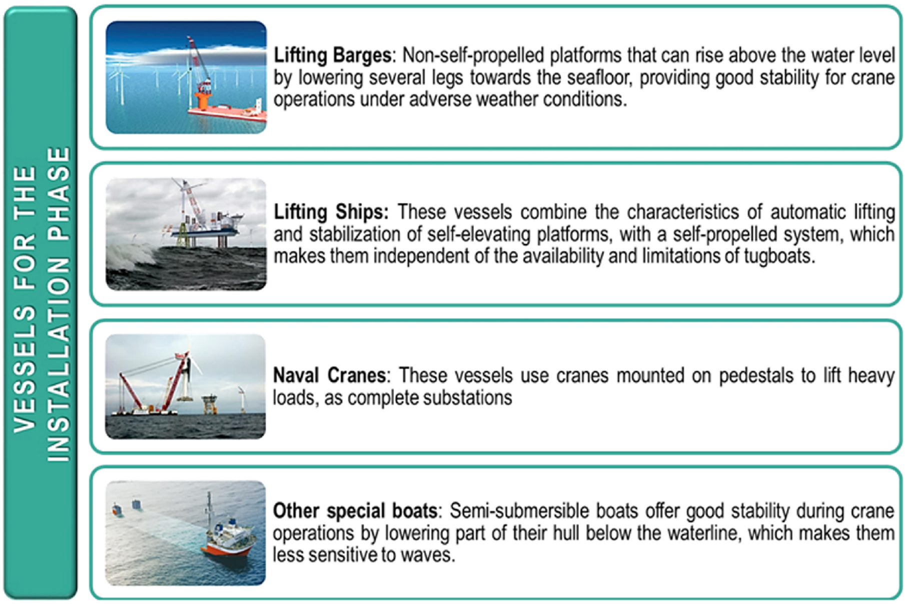
- The means for transporting the FOWT within the port of the shipyard.
- The use of cranes for fabrication and assembly, whose capacity rely on the size and weight of the blocks.
- The available infrastructure for the float-out procedure of the structure.

Regarding wind turbine manufacturing, although it is not an area that shipbuilding industries traditionally share with the FOW sector (excepting the Korean case of HHI), it is worth mentioning that current capabilities for boat manufacturing result in an expertise that encompasses the management of composite materials, which could be utilised in the fabrication of some external pieces of the turbine.

4.3. Opportunities of cross-fertilisation in the installation phase of the FOWTs

According to Tong [22], the installation of FOWTs has two distinct phases: First, the laying of the station-keeping system, and second, the arrival of the wind turbine (already assembled to the tower and the floater) and its subsequent hook-up to the mooring lines. This process is highly-specialised, and for the Colombian case, it would require the involvement of an industrial partner, which is likely to be an international company with experience in this type of deployments.

As discussed in Section 3, the main opportunities for shipyards to support the installation phase of a FOW farm are through the design and construction of suitable vessels for this phase, which are illustrated in Fig. 11.



Lifting Barges: Non-self-propelled platforms that can rise above the water level by lowering several legs towards the seafloor, providing good stability for crane operations under adverse weather conditions.

Lifting Ships: These vessels combine the characteristics of automatic lifting and stabilization of self-elevating platforms, with a self-propelled system, which makes them independent of the availability and limitations of tugboats.

Naval Cranes: These vessels use cranes mounted on pedestals to lift heavy loads, as complete substations

Other special boats: Semi-submersible boats offer good stability during crane operations by lowering part of their hull below the waterline, which makes them less sensitive to waves.

Fig. 11. Examples of ships that could be employed in the installation phase of the FOWTs.

Source: Authors" diagram, adapted from Ingeniero Marino.com [46]

4.4. Opportunities of cross-fertilisation in the testing and commissioning phase of FOWTs

The shipbuilding industry in Colombia has a background in the performance of trials, which are part of the quality assurance process for the final delivery of products to customers. During these trials, the performance of the vessel or floating platform is verified against the initial requirements, which are linked to systems and components specifications.

Some of the procedures used for the Factory Acceptance Tests (FAT) and Harbour Acceptance Tests (HAT) in ships can be applied to the testing phase of the FOWTs, particularly those applied to the assessment of the structural integrity of the floating platform.

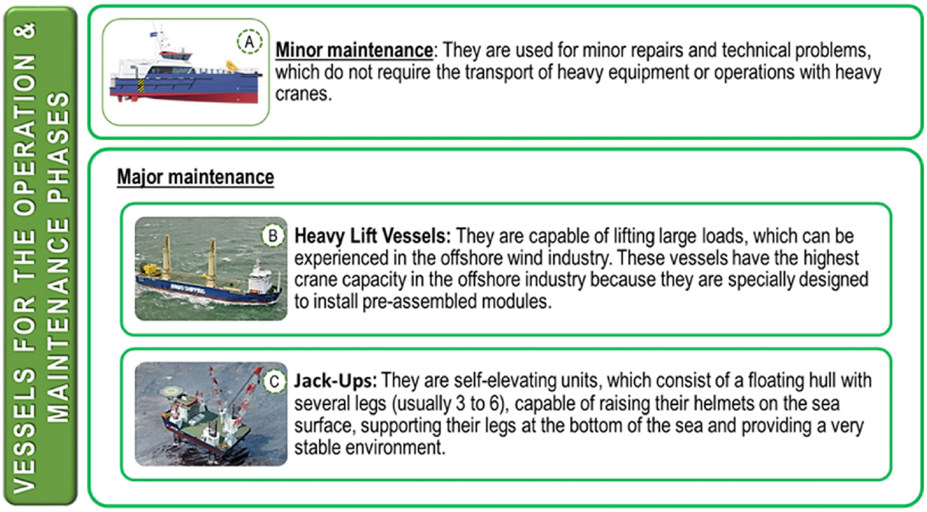
However, there is a knowledge gap in the kind of Sea Acceptance Tests (SAT) applicable to FOWTs, therefore the guidance of an external organisation (for instance, a classification society) will be necessary to carry out this type of test during the commissioning phase of the project. From the authors" perspective, some of the aspects that should be considered during the SATs of the FOWTs are:

- Assessment of the electrical installed power and energy losses due to transmission.

- Stability and seakeeping of the floating structure, i.e. the way the floater behaves when it is exposed to the waves.
- Performance of the electrical generator control system.
- Revision of the auxiliary systems: Blade pitch control, ballast and stabilisation system, electrical distribution.

4.5. Opportunities for cross-fertilisation in the operation and maintenance phases of the FOWTs

The main contribution from the current capabilities of the Colombian shipbuilding industry to the operation and maintenance phases of the FOWTs is through the design and construction of ships equipped to fulfil a diverse range of tasks, from transporting the crew to undertake minor repairs to providing payload handling equipment for major maintenances. The range of support vessels is illustrated in Fig. 12.



Minor maintenance: They are used for minor repairs and technical problems, which do not require the transport of heavy equipment or operations with heavy cranes.

Heavy Lift Vessels: They are capable of lifting large loads, which can be experienced in the offshore wind industry. These vessels have the highest crane capacity in the offshore industry because they are specially designed to install pre-assembled modules.

Jack-Ups: They are self-elevating units, which consist of a floating hull with several legs (usually 3 to 6), capable of raising their helmets on the sea surface, supporting their legs at the bottom of the sea and providing a very stable environment.

A. Source: https://products.damen.com/en/ranges/fast-crew-supplier/fcs-2710

B. Source: https://products.damen.com/en/ranges/heavy-lift-vessel/heavy-lift-vessel-18003

C. Source: https://products.damen.com/en/ranges/jack-up-unit/dg-jack-7140-p

Fig. 12. Examples of ships that could be employed in the operation & maintenance phases of the FOWTs.

Source: Authors" diagram, adapted from Ingeniero Marino.com [46]

4.6. Opportunities for cross-fertilisation in the development of skills for the emergent FOW sector

In addition to the opportunities for cross-fertilisation in the different stages of a FOWT project, it is worth analysing the skills and occupational needs for the FOW sector and how the shipbuilding industry can help to address shortages and gaps in relevant areas.

As stressed by [47], it is quite important to map the diverse occupational profiles that are currently involved within various components of the offshore renewables value chain. Consequently, some previous studies [47]–[49] have identified the key skills and occupations required for the wind energy sector, which have been summarised in Table 3.

From the skills and occupations mapped in Table 3 it is possible to find cross-cutting areas with the shipbuilding industry, especially those related to engineering skills and marine operations. This situation can be evidenced, for instance, in the case of the Scottish OW sector. As reported by [50], the Scottish OW sector has experienced a transfer of marine based skills from other related industries, such as offshore oil and gas. This knowledge base has been a competitive advantage for the development of OW projects like "Hywind Scotland". It is worth mentioning that this knowledge transfer process has been supported by the Scottish government through a specific budget allocation since 2016 (called the "Transition Training Fund").

Table 3. Summary of skills and occupational needs for the FOW sector

Project stage	Related Occupations	Related skills and competences
Equipment manufacture and distribution	• R&D engineers (computer, electrical, environmental, mechanical, wind power design, naval architects). • Software engineers. • Manufacturing engineers. • Manufacturing technicians. • Manufacturing operators. • Quality assurance experts.	• Adjust engineering designs. • Approve engineering design. • Design wind turbines. • Develop test procedures. • Perform test procedures. • Record test data. • Report test findings. • Ensure compliance with safety legislation.
Project development	• Project designers (engineers) • Environmental impact assessment specialists. • Economic/financial/risk specialists. • Social impact specialists. • Lawyers. • Land development advisor. • Land use negotiator. • Wind resource assessment specialists. • Geographers.	• Research locations for offshore wind farms. • Adjust engineering designs. • Design electric power systems. • Examine engineering principles. • Identify energy needs. • Manage engineering project. • Perform risk analysis. • Perform scientific research. • Promote innovative infrastructure design. • Use technical drawing software.

(continúa)

(viene)

Project stage	Related Occupations	Related skills and competences
Construction and installation	• Project Managers. • Electrical, civil, naval and marine engineers. • Wind turbine installers. • Construction electricians. • Power systems technicians. • Construction workers. • Welders. • Quality control inspectors. • Instrumentation and control technicians. • Commissioning engineers. • Transportation workers.	• Align components. • Apply precision metalworking techniques. • Remove inadequate workpieces, • Remove processed workpiece. • Apply health and safety standards. • Assemble electrical components. • Read engineering drawings.
Operation and Maintenance (O&M)	• HSE Coordinator. • Vessel operations Coordinator. • Inspection and maintenance engineers (mechanical, electrical, controls, etc.). • Control technicians. • Managers (commercial, operation and maintenance). • Marine crew. • Field electricians.	• Inspect wind turbines. • Provide information on wind turbines. • Record and report operation data. • Develop cost estimates for O&M activities. • Manage and plan marine operation activities. • Specify needs for non-routine interventions. • Coordinate and exercise emergency response procedures. • Coordinate environmental monitoring requirements.

Source: Adapted from [47], [48], [51].

5. CONCLUDING REMARKS

Indisputably, the Floating Offshore Wind Energy sector shares a common technical background with the shipbuilding industry, with the potential to take advantage of a legacy of knowledge and experience in subjects such as naval architecture, marine engineering, steelwork, and construction techniques for floating platforms. In return, the shipbuilding industry can strengthen its current capabilities by its participation in new areas of R&D derived from the OWE projects, gaining additional understanding of wind interaction with a floating structure, which could lead to further optimisation of existing ship designs.

This process of mutual-enhancement can be capitalised from the opportunities of cross-fertilisation between the Floating OWE sector and the Colombian shipbuilding industry, which were explored in this paper. However, the views presented on this topic were only from a technical perspective, and they did not cover considerations regarding cost and risk, which are two crucial aspects for any project and, hence, must be tackled in a further study. In the case of a FOWT project, the cost and risk are intrinsically related to the type of floating platform, given that not all the types are in the same stage of development. A Multi-Disciplinary Analysis and Optimisation (MDAO) methodology would be strongly recommendable for future analyses, allowing for the integration of the technical performance dimension with the cost and risk domains. This approach is currently employed during the concept exploration phase in the design of naval vessels.

From the literature findings and the review of the case studies, it could be observed that the spar-buoy and the semi-submersible types are more mature concepts, compared to the TLP-type. Moreover, special attention should be given to the challenges or design/construction constraints posed by a particular type of floating structure, since some of them could turn into requirements for the physical infrastructure of the shipyard (e.g. cranes, ship-lifting appliances, workshop layouts, etc.).

On the other hand, although there are multiple areas where the shipbuilding industry in Colombia could participate in the value chain of the Floating Offshore Wind Energy sector in Colombia, it is foreseeable that the main contribution of this industry would be the design and construction of vessels for the installation and operation/maintenance of the FOWTs, given the relationship of these activities with its core business.

Also, it is important to highlight the relevance of having technological partners to support the diverse processes throughout the value chain of the FOWTs. The triple helix model of innovation (i.e. academia, government, and industry) has been widely adopted in previous FOWT developments worldwide. Therefore, is it recommendable to strengthen the synergies between these three actors in the Colombian context. A clear regulatory framework will also contribute towards consolidating these synergies in the FOWT value chain, looking to achieve innovation through cross-fertilisation of the knowledge and experience of the different stakeholders.

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