OFFSHORE WIND TECHNOLOGIES FOR CHILE

PERSPECTIVES AND CHALLENGES

MERIC
MARINE ENERGY RESEARCH & INNOVATION CENTER
by ENERGIAMARINA SpA

Universidad Austral de Chile
Conocimiento y Naturaleza

OFFSHORE WIND
TECHNOLOGIES FOR CHILE:
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Offshore Wind Technologies for Chile
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Introduction

Offshore wind energy is a renewable energy source with great potential worldwide, with strong development in Asia and Europe in recent years. It is expected to grow by 15 to 21 gigawatts (GW) per year between 2025 and 2030 [1], thanks to the opening and implementation of new markets such as America, Oceania and the Asian continent.

The offshore wind energy resource has a high quality and a large number of areas available for exploitation. Although the costs of offshore wind energy are still higher than those of other onshore renewable energy sources, significant reductions are projected, which will be accompanied by the development of economies of scale, technological innovations and mass production [2].

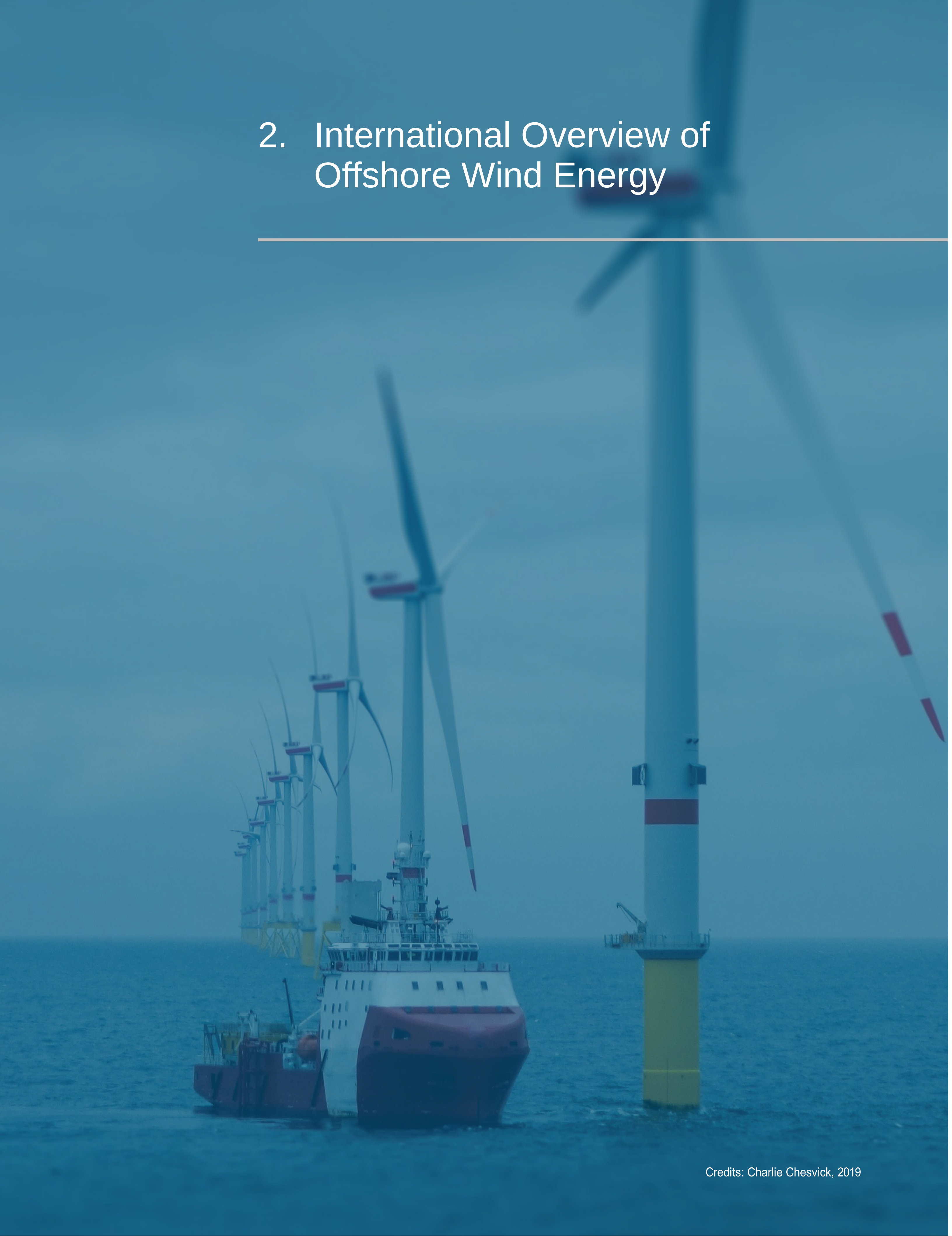
Currently, the offshore wind sector mostly uses bottom-fixed devices, installed at depths of less than 50 metres (m). Recent innovations in floating devices, which are about to enter the commercial phase, have considerably expanded the geographical areas that are compatible with this type of technology, especially in countries that do not have an extensive continental shelf, as is the case of Chile. In Chile, the estimated technical potential of offshore wind energy is 957 GW, of which 14% corresponds to bottom-fixed offshore wind turbines, and 86% (826 GW) to floating wind turbines [3].

One of the main challenges for the coming years is to reduce costs (CAPEX and OPEX) and improve manufacturing, installation and maintenance capabilities [4], in order to ensure a sustained reduction in power generation costs. The great potential for economies of scale in this industry and innovation in manufacturing, installation and maintenance processes allow a cost reduction path to be envisaged in the medium and long term.

To take advantage of the offshore wind resource in Chile it is necessary, in addition to an active participation in the development of technologies and their cost reduction, to address and resolve specific local issues, such as aspects linked to manufacturing capacities and maritime services, and the creation of a regulatory framework that promotes the development of the sector in harmony with other uses of the maritime territory and coastal regions.

This document was built on the basis of diverse research and experiences acquired throughout the execution of the MERIC project, seeking to contribute to the development of offshore wind energy in Chile.

Credits: Aerovista Luchtfotografie, 2020



2. International Overview of Offshore Wind Energy

Credits: Charlie Chesvick, 2019

In recent years, the offshore wind sector has undergone significant geographical and technological expansion.

Geographically, the sector has gone from being concentrated in Europe, to a strong development in Asia and, more recently, in North America and Oceania. In terms of technology, there has been significant progress in terms of turbine capacity and a growing interest in floating wind technology, which, in addition to technologies fixed to the bottom, allows access to previously inaccessible maritime spaces.

INSTALLED CAPACITY BY REGION

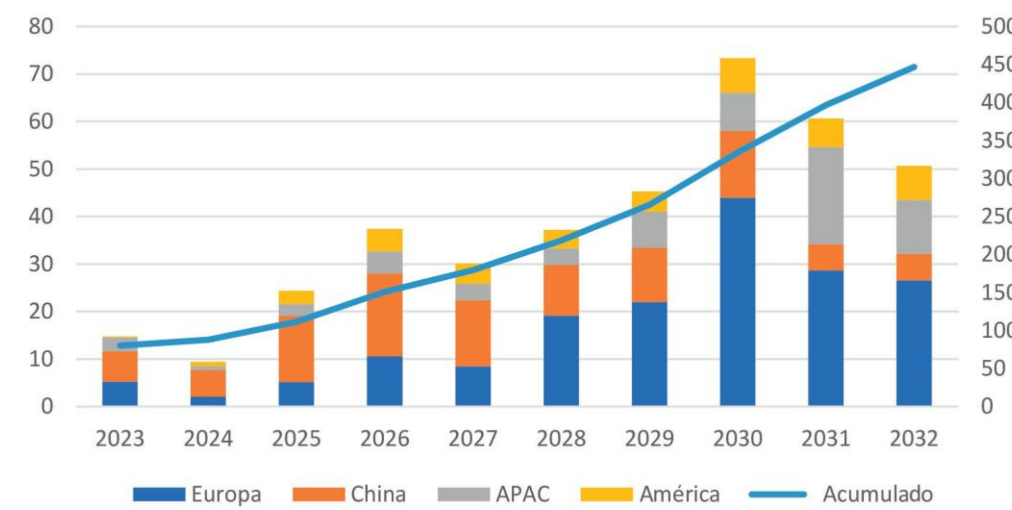


Fig. 1: Global projection of offshore wind installed capacity (GW). Source: Westwood Global Energy Group (2023) [5].

According to information compiled by Westwood Global Energy Group (Fig.1) [5], the sector's projections foresee a 700% increase in installed capacity, from 63 GW in 2022 to nearly 450 GW in 2032. Of this total, around 6% is expected to be of the floating type, a percentage that will continue to increase in the coming decades. At the regional level (Central and South America), there is growing interest in this type of energy, particularly in Brazil, Colombia [6] and Mexico [7], of which the former has made the greatest progress, with more than 171 GW submitted to its environmental assessment system [8].

A World Bank study [9] identifies a technical potential of more than 7100 GW of offshore wind energy in Latin America, with Argentina, Brazil, Chile and Mexico being the four countries with the greatest potential. Particularly the cases of Argentina and Chile contemplate more than 1800 GW and 950 GW, respectively. However, there are still no policies and/or strategies related to this energy source, which in the case of Chile is striking considering its highly favourable public policies for the development of renewable energies in general.

3. Offshore Wind Energy in Chile: Opportunities and Challenges

For the implementation of offshore wind energy technologies on a commercial scale, there are several key aspects that have both technical and economic implications and that can generate various risks for the correct development of a project of this type. The aspects presented in this section are related to the wind resource, bathymetry and environmental conditions, both operational and external. Also, regulatory, environmental, social and other technical aspects related to manufacturing, installation and maintenance capacity.

Credits: Departamento de Geofísica, Univ. de Concepción

3.1 Resource

According to information provided by the World Bank, Chile is positioned as an area of high potential for the development of offshore wind projects (Fig. 2).

In our country, onshore wind energy has managed to position itself as a fundamental renewable source to achieve decarbonisation of the electricity matrix, reaching an installed capacity of 4605 megawatts (MW) in September 2023, equivalent to 13.1% of the total, only surpassed by solar photovoltaic energy (26%) and natural gas (14%) [10]. While this is an indicator of the high existing wind potential, when reviewing the geographical distribution of these installations, we see that they are mainly concentrated in the northern zone, with 2749 MW between the regions of Antofagasta and Coquimbo, and the central-southern zone, with 1388 MW in the regions of Biobío and Araucanía. As mentioned in the report issued by the Ministry of Energy and the German technical body GIZ [11], the available potential decreases significantly when considering territorial restrictions (slope of the land, proximity to urban areas, among others) and technical restrictions (optimal plant factor and electricity transmission). In this context, and considering the more than 4000 kilometres (km) of coastline, the potential of offshore wind in Chile should be taken into account.

Off the Chilean coast, surface winds are determined on a large scale by the presence of both the South Pacific anticyclone, which favours the arrival of southerly winds on the coast in the northern and central areas, and the low pressure belt that generates cyclonic circulation in the mid-latitudes. These winds propagating over the sea without any barrier have a greater potential than on land. According to the study Mattar & Borvorán (2016) [12], which shows the results of the first estimation of the offshore wind resource for central Chile, there is a potential of around 30 gigawatt-hours (GWh) of annual generation and a plant factor of more than 40% for a reference turbine of 8 MW.

Despite the potential of this resource, a state of the art review of offshore wind energy in Chile shows how little this topic has been explored, with only a few studies referring to the existing potential and its development [3, 12-16]. Among them is the study Mattar & Guzmán (2017) [13], which analyses the techno-economic feasibility of offshore wind energy in our country, and highlights the area between 30º and 32ºS due to the balance between power density and the technical conditions of plant factor and performance, which make it a site of interest to be considered.

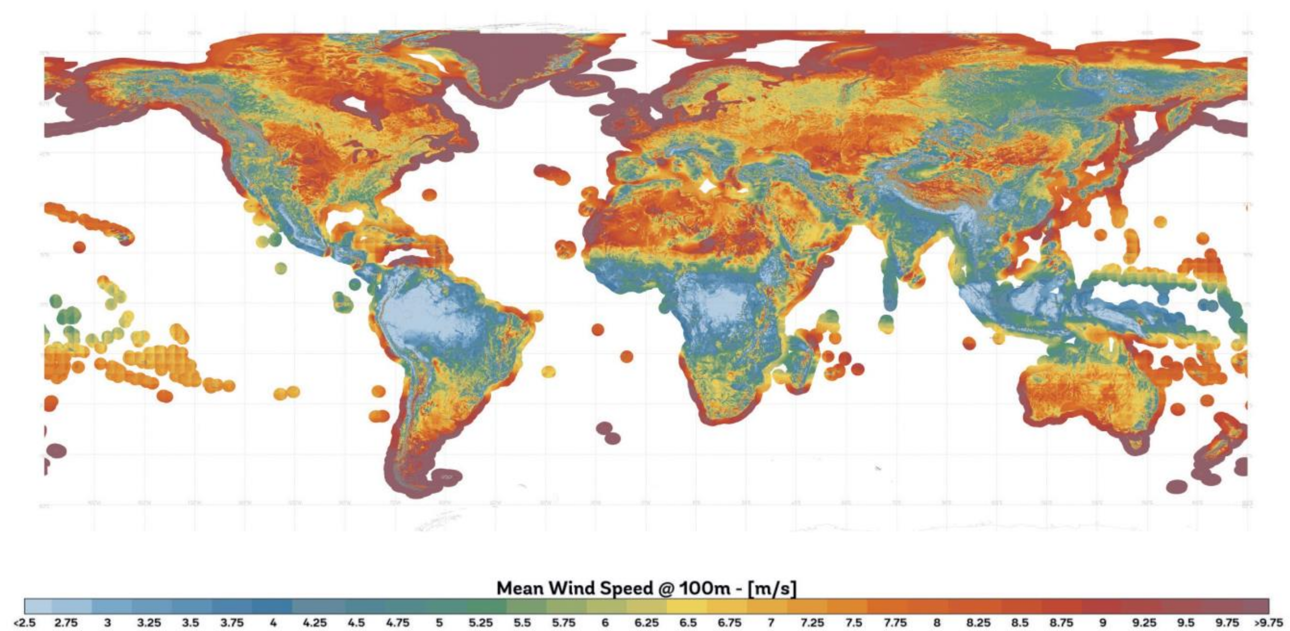


Fig. 2: Global onshore and offshore wind potential. Source: World Bank

3.2 Operational and Extreme Conditions

For the development of an offshore wind energy project, along with a detailed characterisation of the wind resource, it is necessary to describe the sea conditions, as they have a strong impact on the design of the foundation, in the case of bottom-fixed technologies, and of the platform and its mooring systems, in the case of floating technologies.

Extreme sea conditions, usually associated with return periods of 50 to 100 years, have a strong impact on the structural design. On the other hand, operational sea conditions, i.e. the set of sea states representative for most of the project's useful life, have an impact not only on power generation, but also on structural design (specifically on fatigue analysis) and on the design of installation and maintenance operations, which in turn have an impact on the availability factor (percentage of time the plant is operational).

In offshore energy projects, maintenance costs can exceed 20% of the total project cost [17] and are affected by the operational conditions of the chosen site and the types of vessels used. The Offshore Wind Access Report 2022 [18] concludes that there are a wide variety of Crew Transfer Vessels (CTV's) used for operation and maintenance (O&M) tasks at offshore wind farms, which allow access under sea states with significant wave heights of up to 1.5 - 2 m.

Thus, the percentage of occurrence of sea states in which it is possible to perform O&M is an important factor to evaluate, because it directly affects the plant availability and thus the final cost of energy [19].

To exemplify, four reference sites have been selected: two in Europe and two in Chile:

- Celtic Sea, off the south-west coast of England (50.8°N, 7°W)
- Atlantic Ocean, off the coasts of central Portugal (39°N, 9.8°W)
- Pacific Ocean, off the city of Valparaiso, Chile (33.6°S, 71.8°W)
- Pacific Ocean, off the city of Concepción, Chile (37°S, 73.6°W)

Fig.3 shows, for each of these reference sites, the percentages of occurrence of significant heights less than 2.5, 2.0, 1.5 and 1.0 m. For example, if a certain type of maintenance requires a significant height of less than 1.5 m, it can be seen that the reference sites in England and Portugal have a marked seasonal cycle, with percentages of occurrence greater than 50% in the summer months. On the other hand, the sites in Chile show a low seasonality. In the site off the coast of Valparaíso, the percentage of occurrence of significant heights below 1.5 m is close to 30% throughout the year, while in Concepción, this value is reduced to less than 20%.

Based on this analysis, it can be inferred that offshore wind turbine maintenance operations in Chile will have less and shorter weather windows than other parts of the world, or that it will be necessary to develop technologies and procedures adapted to these environmental conditions.

In addition, the amount of storm surges (marejadas) in Chile has been increasing throughout the country [20], in addition to the increase in intensity and frequency during the last decades. If in the middle of the last century there were 5 extreme events per year, today there are 20 per year, even in the summer months [20-23]. The increasing trend of significant wave height between 1980 and 2015 is 10-20% (0.1 - 0.4 m) [22, 23], while the significant heights of extreme waves showed an increasing trend of 0.01 metres per year (m/year) between 1985 and 2018 [24]. Also, the historical mean for a 100-year return period is 3.4 m (1985-2004), whereas for the projection between 2026 and 2045, it is 4.8 m, representing an increase of 41%. An example of such extreme events was the 2015 storm, which left considerable damage in Coquimbo, Viña del Mar and Valparaíso, with losses of at least US$1,862,000. The maximum significant wave height recorded was 7.23 m, and there was also an impact on coastal morphology, such as beach erosion, undercutting and shoreline retreat [25].

The aforementioned factors are key points to consider when analysing potential sites for marine energy development in Chile, as they have an impact on costs, waiting times, accessibility, among others.

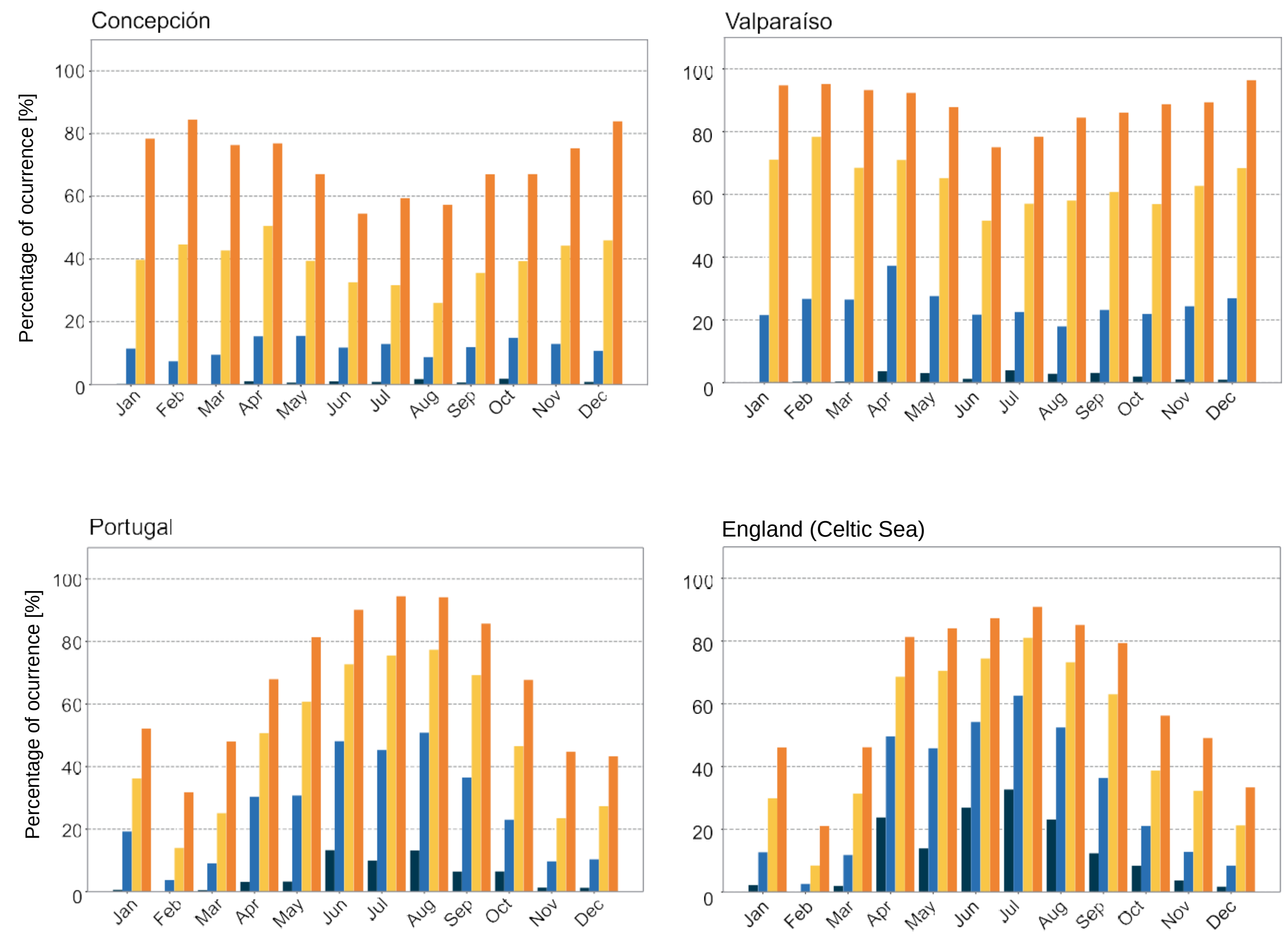


Fig.3 Percentage of time that the reference sites in Concepción, Valparaíso, Portugal and England have significant wave heights lower than:

2.5 m. 2.0 m. 1.5 m. 1.0 m.

3.3 Bathymetry

The development of the offshore wind industry needs to be located within a range of specific depths that allow for the technical and economic feasibility of the project (Fig. 4). For offshore turbines fixed to the bottom, a maximum depth of around 50 m is considered for the project to be economically viable. Above this depth, the installation of floating wind turbines is feasible, although some of these technologies require even greater minimum depths. As for the maximum limit, it is expected that these floating devices can be installed in water depths of up to 800 or 1000 m, although to date the deepest project is 300 m (Hywind Tampen in Norway).

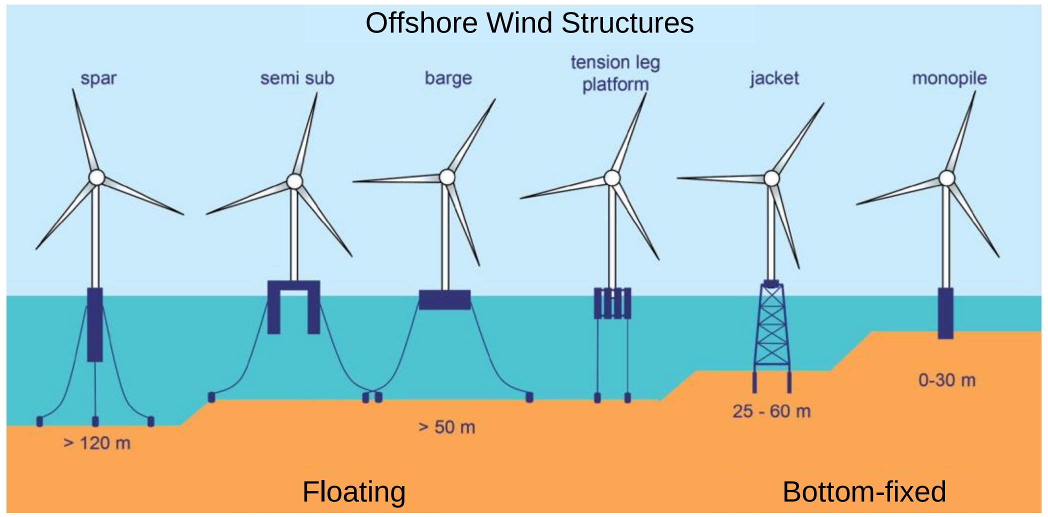


Fig. 4: Offshore wind structures and typical installation depths. (Source: own elaboration).

The continental shelf is the natural extension of the territory that extends under the sea and is characterised by being relatively flat. The large extension of the continental shelf in northern Europe, together with the existing wind potential in this area, has enabled the booming development of the offshore wind industry, mostly using bottom-fixed turbines due to the shallow depths of the sites.

But unlike the optimal conditions in the European region and elsewhere in the world (e.g. China, the east coast of the United States, Brazil and Korea), Chile has a very different bathymetry. Despite our vast maritime territory, depths increase rapidly as we move away from the coast (Fig. 5).

From 33ºS to the north, our continental shelf is almost non-existent [27], while between 33ºS and 43ºS it has an average width of between 30 and 40 km, with the areas of greatest extension located off Isla Mocha (Biobío region) and Isla de Chiloé (~60 km).
This macrozone, which extends from the Valparaíso region to Los Lagos, reaches maximum depths of 150-300 m [28]. Beyond the shelf boundary, the relief drops more steeply, reaching up to 8000 m depth in the oceanic trench.

In this context, despite such comparative disadvantages, the characteristics of south-central Chile present interesting conditions for the future development of the offshore wind industry.

Fig. 5: Chilean continental shelf from Arica to Chiloé. Data extracted from GEBCO [26]

3.4 Considerations

Environmental impact

The environmental impact of the offshore wind industry, as well as of any production process, needs to be studied in order to establish regulations to minimise and/or mitigate it. In a recent study of Galparsoro et al. (2022) [29], the existing interactions between wind turbines and marine ecosystems have been summarised.

Among the moderate/high negative impacts is the damage caused by turbines to marine birds and mammals, such as mortality and displacement, and to the structure of ecosystems.

On the other hand, mention is made of certain positive impacts such as the use of the structures by marine species as artificial reefs and the mitigation of the impacts of trawling due to its prohibition in areas close to the installations for safety reasons.

As emphasised in this research, environmental impacts have spatial variability, i.e. they vary from site to site depending on the conditions there. Therefore, the development of the offshore wind industry in Chile will require local studies and direct monitoring to gain a deeper understanding of the marine ecosystems and what they may face.

Visual impact

Another aspect that is important to consider before choosing a site for an offshore wind energy project is the visual impact.

In countries where the offshore wind industry is more advanced, the location of installations close to the coast has generated rejection because of the disturbance to the landscape. Although visual impact is subjective, and therefore difficult to quantify because it is subject to people's emotions, recent studies suggest some considerations to improve the acceptability of the population.

In the Mishima & Mishima (2023) research [30], it is concluded that the spatial location of turbines with a more symmetrical configuration would generate greater acceptance. Similarly, the work of Sullivan et al. (2013) [31] suggests that turbines with hub heights between 67 and 90 m. located more than 40 km from the coast are only visible with effort; at distances close to 29 km they are occasionally visible to the eye; and, at less than 16 km they become a major focus of visual attention.

In this case, for the siting of offshore wind projects in Chile, it would be beneficial to consider distances away from the coast that generate less visual impact.

Multiple uses of maritime space

Another consideration to take into account is the multiple use of maritime space, since our vast ocean is home to economic, recreational and environmental conservation interests, among others. Existing regulations allow different entities to be granted part of the maritime space located within the territorial sea (12 nautical miles from the coast) for its use, safeguard, exploitation and/or administration. Thus, it is possible to find Aquaculture Concessions, Benthic Resources Management and Exploitation Areas (AMERB), Marine Protected Areas (MPA), Marine Coastal Spaces of Indigenous Peoples (ECMPO, Lafkenche Law), and more.

The regulation currently prevents the renewal and processing of new concessions in areas where ECMPO areas have been requested or granted [32, 33]. By 2023, these coastal areas amount to more than 200,000 hectares and there are more than 2 million hectares requested for management, almost entirely located from the Biobío region to the south [34].

In the international context, in European seas with large offshore wind energy development, conflicts have been identified with the fishing industry, especially with trawling, due to the displacement of their work and its economic consequences. And with the projected expansion of the offshore wind industry, such events are expected to increase significantly in the long term, if actions are not taken to allow the coexistence of both activities [35].

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3.5 Manufacturing, Installation and Maintenance Capabilities

To ensure the technical and economic viability of future offshore wind energy projects in Chile, it is necessary that a significant part of the manufacturing of the structures is carried out in our country. It is also necessary to ensure that the installation, maintenance and decommissioning work can be carried out with the infrastructure and equipment available in Chile or, alternatively, to consider economies of scale that allow the incorporation of this equipment or infrastructure in the long term.

The fabrication, installation, operation, maintenance and decommissioning of a floating wind platform or farm can be summarised in the following diagram (Fig. 6):

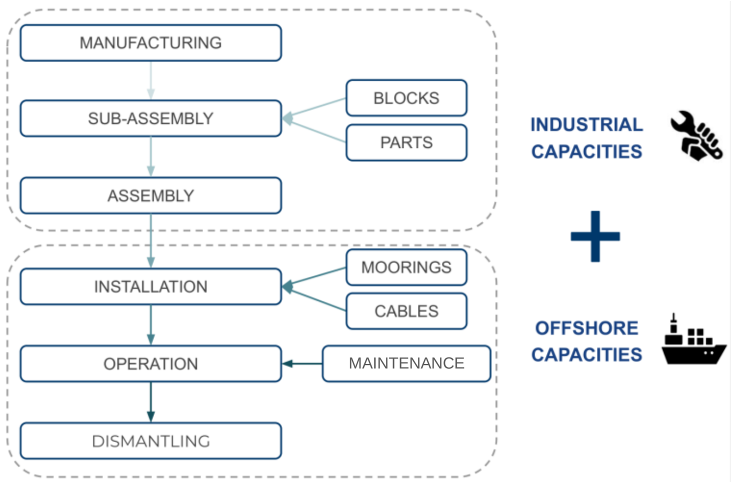


Fig.6: Diagram of manufacturing, installation, operation, maintenance and decommissioning of a floating wind platform. (Source: own elaboration)

Due to the design, dimensions and mass, the fabrication, assembly and integration of the main elements are considered to be more challenging for domestic shipyards, although this may require a case-by-case analysis.

While the facilities and much of the required supply chain may currently exist in the shipbuilding field, the lifting, manoeuvring and launching capabilities of large platforms may not.

In terms of offshore installation, maintenance and decommissioning operations, it is estimated that these can be a complex challenge. Performing maintenance in the marine environment can be costly, time-consuming and risky [36]. On an offshore wind platform, there are multiple components that will require regular maintenance and inspection, so it is important to have safe and effective means of access. For these purposes, specialised vessels are available, as well as means of transferring personnel and cargo to minimise the risk of this critical operation. Considering that marine operations have a strong impact on the total investment in a project of these characteristics, their consideration is crucial when assessing the feasibility of a technology for its application in Chile.

Based on an analysis of the various technologies currently available and the infrastructure and equipment available in Chile, the following key aspects of the installation, maintenance and decommissioning of the systems were identified:

Lifting and mobilization requirements

Due to the size of most floating wind platforms (larger than Chilean-built vessels and naval craft, particularly in width), it is considered that there are significant limitations to the lifting and onshore movement of these structures, restricting the number of locations in which such devices could be mounted. These limitations are both in the infrastructure (fabrication yards, launch stands, etc.) and in the equipment required (e.g. cranes and heavy transport systems).

As for the availability of sea transport options, the alternatives are limited. Chile does not have special vessels such as Heavy Lift Ships or Anchor Handling Tug Supply (AHTS) vessels, normally used for transporting large items on deck, so the options are limited to the use of pontoons or barges or towing, with the respective limitations that this implies. For offshore lifting operations, the options are limited to a single floating crane ("Yagana", with a lifting capacity of 350 tonnes) and pontoons on which smaller land mobile cranes can be installed. Considering also that none of these options have been designed to perform operations under the typical conditions found in the open sea off the Chilean coast, waiting for suitable weather windows could limit or significantly delay these operations.

Due to the above, it is considered that technologies that do not require lifting operations in the water or transport on deck, i.e. those that can be towed afloat to the installation point, present a better compatibility with the conditions currently found in Chile.

Requirements for the installation of platforms and their mooring systems

A decisive aspect for the installation of platforms and their anchoring elements is the support infrastructure for marine operations. The selection of the home port, the available support fleet and the support equipment must be appropriate and compatible with each other.

The selection should consider aspects such as: platform design, seabed characteristics, prevailing environmental conditions, and available installation methods and strategies.

Depending on local capabilities and conditions, it is advisable to have a holistic view from the beginning of the project and throughout operational planning. In addition, by integrating it with the selection of port, vessels and support equipment, significant cost reduction opportunities can be generated.
Depending on the type of technology, the requirements for the installation of the platform or its mooring elements are highly variable and regulated [37]. In the case of platforms with conventional anchoring systems (e.g. by catenary), the precision requirements for anchor location and the usual installation operations are compatible with the working vessels frequently encountered in Chile, such as tugboats, barges or pontoons.

For technologies that require high precision in the location of their anchoring components, the general practice is to use vessels with DP (Dynamic Positioning) systems, of which there are few units in Chile. If this requirement is coupled to a lifting operation, for example, of a large base to fix the device to the seabed, the intervention of large offshore supply vessels (OSVs) may be necessary, which are usually available in countries with an here Oil & Gas industry exists. In the case of Chile, this could make a project economically unfeasible.

On the other hand, technologies that do not require high-precision positioning are considered to be more compatible with the current conditions in Chile. In the medium term, it is also considered feasible to adapt vessels or manoeuvring equipment for the installation of small, high-precision elements, which could also be applied in a similar way as in the aquaculture industry.

Maintenance requirements

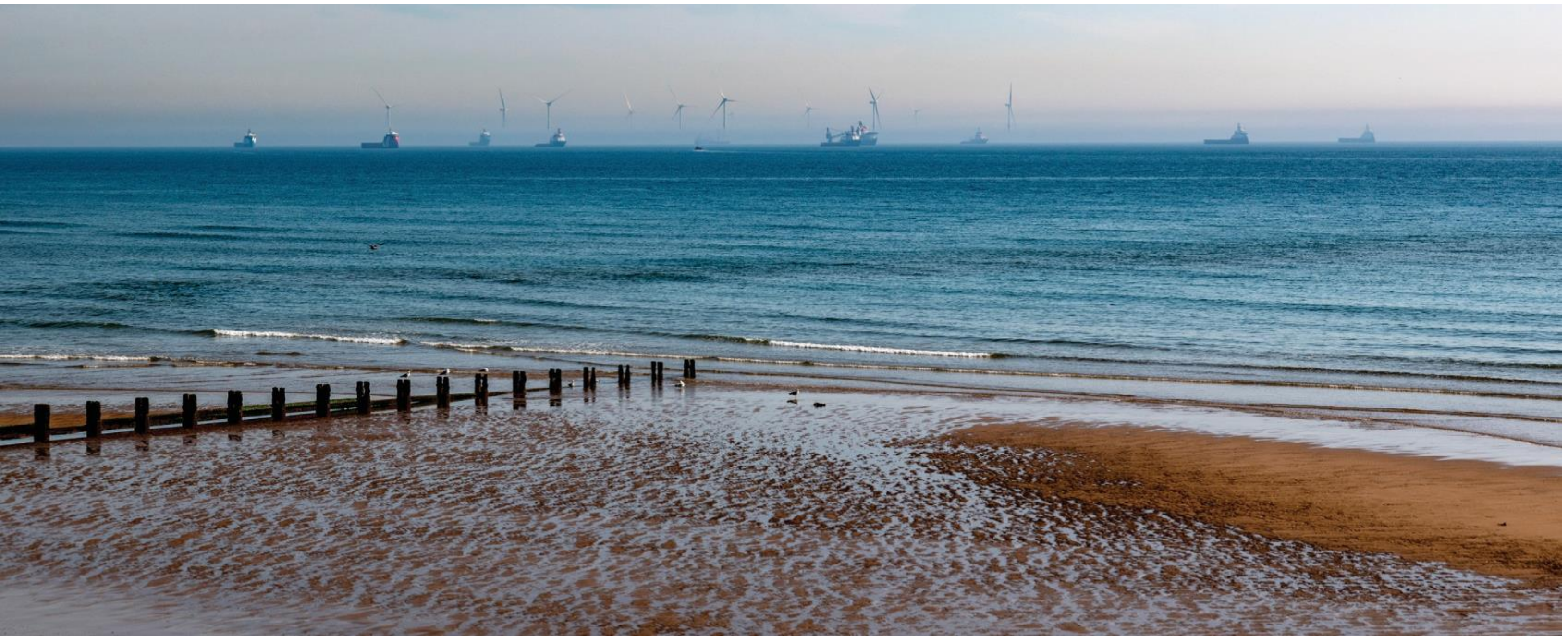
This analysis identifies three types of maintenance operations: on shore, on port and on site. Shore-based maintenance, also referred to as dry docking, requires similar capabilities to manufacturing, which can be costly.

While for major turbine maintenance - such as blade replacement - port-based maintenance is a simpler option, it requires specific conditions in terms of port depth, lifting capabilities and access, which can significantly increase costs. For these reasons, there is a trend of many developers seeking to minimise these types of maintenance by carrying out most of it on site.

On-site maintenance can be related to low-complexity underwater work such as inspection with ROVs (remotely operated underwater vehicles), to deep-sea work or welding tasks that require specialised divers, involving high costs and risks. Likewise, on-site maintenance requires inspection and maintenance work on board the wind platform, which in turn will require a high-risk transfer of personnel and/or material.

There are several rules and standards that provide guidelines for the design, planning and execution of this type of marine operations [38-40], establishing technical and environmental criteria and whose application may present challenges considering the typical wave and wind conditions in Chile, as well as the limitations imposed by the support vessels and systems usually available. In this context, platforms that require minimal maintenance on land (e.g. by using materials such as concrete) are considered to be more compatible with the conditions in Chile. A holistic design, including the appropriate design or selection of support vessels and equipment for this work, is also considered to be of great importance.

Credits: Rab Lawrence, 2018



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3.6 Regulatory Framework and Marine Spacial Planning

For the successful development of the offshore wind sector in a given country, it is necessary to have an adequate regulatory framework that establishes limits and requirements for developers, reflecting the local long-term renewable energy strategy, and providing certainties that encourage the high initial investment required for this type of project. In countries with a developed offshore wind sector, it is observed that all of them have a specific regulatory framework for this activity that includes technical, environmental and social aspects, with a strategic view not only to an energy policy, but also to territorial planning.

This regulatory framework can include multiple elements such as laws, national plans, regulations and standards, which provide the conditions for obtaining permits, such as marine tenders, specialised government agencies, injection of energy into the grid through regulated tariffs, priority purchase or other measures, environmental and social requirements such as activity-specific environmental laws, and more.

Denmark, Germany, the Netherlands, the United Kingdom, Belgium, France and more recently China, the United States and South Korea are countries that have a regulatory framework and planning for their maritime territories and Exclusive Economic Zones (EEZs), having several of them projects already in operation, while others are strongly developing the activity. At the Latin American level, Colombia, which has already presented a development strategy, and Brazil, which has a territorial planning and is about to present a law to regulate this sector, stand out [41].

In the case of Chile, to date there is no specific regulation for the development of offshore wind energy projects. Although current legislation is in line with the United Nations Convention on the Law of the Sea (UNCLOS [42], ratified by Chile in 1997), which grants the State sovereign rights to explore, exploit, conserve and administer the natural resources of the territorial sea and the EEZ, the lack of specific regulations makes it difficult to plan and encourage the activity in the long term.

In the EEZ, Chile does not yet have specific regulations or a long-term strategy, which is reflected in the absence of this issue in the decree enacting the "National Oceanic Programme", signed in 2023 by the Minister of Foreign Affairs [43]. This situation may slow down the development of the offshore wind sector in the short and medium term, but it opens up the opportunity to build a robust regulatory framework in the long term that takes into account the decarbonisation objectives assumed by the State, and addresses relevant issues that promote the activity under favourable conditions for all parties.

4. Analysis of Potential Sites and Applications in Chile

Credits: Eachat, 2019

This section aims to recommend, in a general way, sites that are interesting to consider in techno-economic studies that seek to develop offshore wind energy in Chile, which should be complemented with environmental and social studies. Other applications which could have a niche potential in Chile, in addition to the injection of energy into the electricity grid, will also be presented. For this analysis, the information presented in the previous section was used as a basis, where specific aspects of our country and its offshore wind potential are presented.

The existing wind resource off the coast of Chile presents good conditions, especially in the central and southern areas, where the average wind speed is close to 9 metres per second (m/s) at a height of 100 m (Fig. 7, left).

In terms of bathymetry, the northern zone does not present depths that make the development of the offshore wind industry viable on a large scale, due to the fact that the continental shelf is almost non-existent. However, from the Valparaíso region to the south, conditions are favourable for these projects, as the continental shelf is more extensive.

The bathymetry map showing part of the Chilean territory (Fig. 7, right) shows depths ranging from 0 to 250 m, with a greater area between 50 and 150 m, which favours the use of floating platforms over those fixed to the bottom. In the same figure, the territorial sea is delimited by a black line which, as explained above, is an area with a large number of concessions granted or being processed, which at present could cause difficulties when requesting permits to locate a project or power lines to land.

The installation of a wind farm less than 16 km from the coast could cause visual impact, leading to social conflicts, especially if it is close to inhabited territories. For this reason, areas of the continental shelf west of the territorial sea boundary (~ 19 km from the coast) are recommended as more suitable.

In relation to port and industrial capacities for installation and maintenance, most of the country's most important ports and shipyards are located between 30º and 41ºS [45]. These include San Antonio and Valparaíso (Valparaíso region), and the ports of San Vicente and Coronel (Biobío region). As for shipyards, among the largest and most important are ASMAR in Talcahuano (Biobío), and ASENAV in Valdivia (Los Ríos). It is important to consider these capacities when choosing potential sites, due to the need to build and integrate floating structures, specialised vessels, and maritime and port services.

Another relevant aspect to reduce costs when siting an offshore wind project is that its location is close to consumption centres. According to demand projections for the year 2042, it is estimated that this will amount to 8.5 terawatt-hours (TWh) in the Valparaíso region, 7.6 TWh in Biobío and 1.6 TWh in Los Ríos [46].

In conclusion, these three regions have great potential for the development of the offshore wind industry, as they have good wind resources, important ports and/or shipyards, and consumption centres close to the coast (Fig. 7). In terms of bathymetry, there are few areas with depths compatible with platforms fixed to the bottom, while there are large sectors with depths compatible with floating platforms, especially in the regions of Biobío (Concepción) and Los Ríos (Valdivia).

Finally, when considering industrial and port development, it is observed that Bío Bío has the greatest compatibility for the development of this industry in the medium term, which could be reached by Los Ríos in the long term.

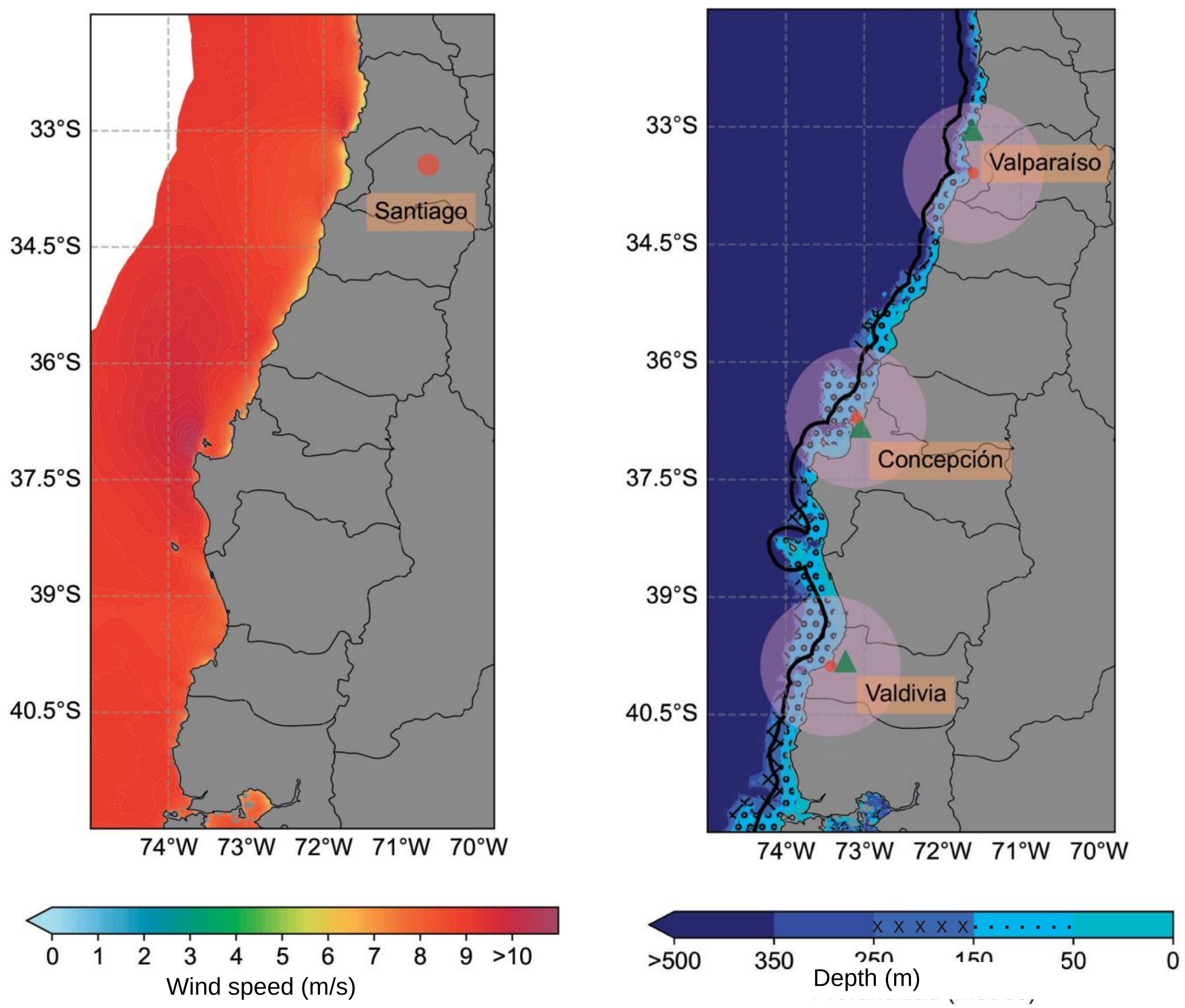

Fig. 7: Central and southern regions of Chile with: (left) offshore wind resource. Data extracted from Global Wind Atlas [44], y (right) bathymmetry, limit of territorial seas (12 nautical miles, black line), regional main coastal cities (green triangles) y near-by ports with 100 km radius (red circle).

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Complementary to the development of offshore wind farms for grid power injection, Chile has interesting niche applications where different offshore activities could be integrated, such as aquaculture, desalination and green hydrogen production.

In the case of aquaculture, there is a strong interest in developing offshore aquaculture or aquaculture in exposed areas, which requires significant technological innovations and higher energy requirements in terms of both quantity and autonomy [47].

In the case of desalination, which is becoming increasingly important in Chile, especially - though not exclusively - in the north, there is a growing interest in using renewable energy sources, in addition to the first developments of floating desalination plants that could be integrated into offshore wind farms.

The development of green hydrogen in Chile is perhaps the niche with the greatest potential in the long term, considering that the first integrated floating wind energy and hydrogen production plants are already under development [48]. While the integration of these technologies is still at a very early stage, their implementation in Chile could reduce the pressure on onshore wind projects in the Magallanes region and expand production capacities in the vicinity of processing and consumption centres.
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5. Tools and Capacities Developed by MERIC

In the search to generate capacities for the development of marine energy in Chile, and in particular offshore wind energy, the MERIC Centre together with the Wave & Towing of Universidad Austral de Chile (CEH-UACh) have developed tools and methodologies that contribute to the knowledge of these projects and the specific conditions that exist in our country.

Credits: Charlie Chesvick, 2018

5.1 Adapt-ORE

Adapt-ORE is a tool developed by the MERIC Centre through the Research Line "Adaptation of Marine Renewable Energy Technologies to Local Conditions in Chile".

It is based on a geo-referenced, time-domain discrete event simulation model designed to assess the life cycle of marine renewable energy projects and compare different sites, technologies and O&M strategies. Adapt-ORE allows the user to create project scenarios by entering environmental (behind cast) and operational (port closure criteria, etc.) parameters concerning the sites, vessels, ports and devices of interest, which will be used as input to evaluate the performance of the devices at a site, among other relevant indicators.

Waiting times for accessing a device due to unsuitable environmental (wave and/or wind) conditions or for executing maintenance tasks increase the downtime of a turbine, causing a direct impact on the generation of electrical energy, and therefore on economic gains. Considering that the performance of maintenance is subject to required environmental and operational limits, and to the characteristics of the vessels and devices involved, Adapt-ORE integrates in the evaluation of projects the hydrodynamic characteristics of both the devices and the vessels, which are obtained through model scale experiments and numerical simulations. This allows to obtain operability curves for the vessel, which will define the limiting sea state at which it can operate at the time of maintenance [49]. As shown in the Adapt-ORE flowchart (Fig.8), the feasibility of departing from port and performing the scheduled tasks are evaluated for each simulation time step when maintenance is required.

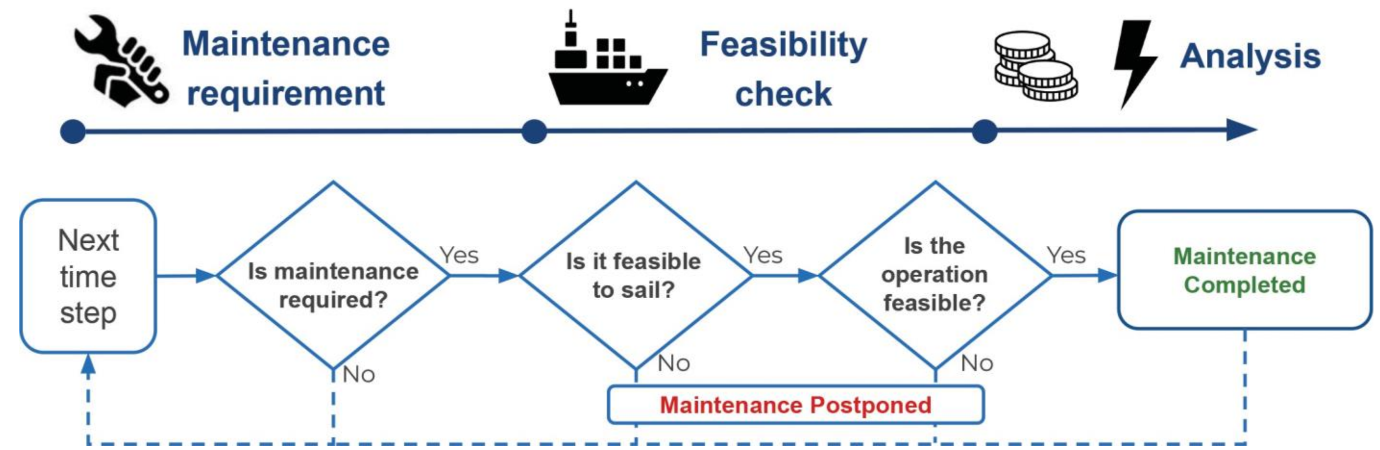

Fig. 8. Flowchart of the Adapt-ORE discrete event model for assessing the feasibility of maintenance.(Own elaboration)

Adapt-ORE delivers a series of results of the marine energy project evaluation, which are displayed on the interface as synthesised information and graphs (Fig. 9), or saved in output files. These results include: total energy generated throughout the project, total waiting times in port and on site, energy lost due to maintenance, maintenance costs and weather windows for the site.

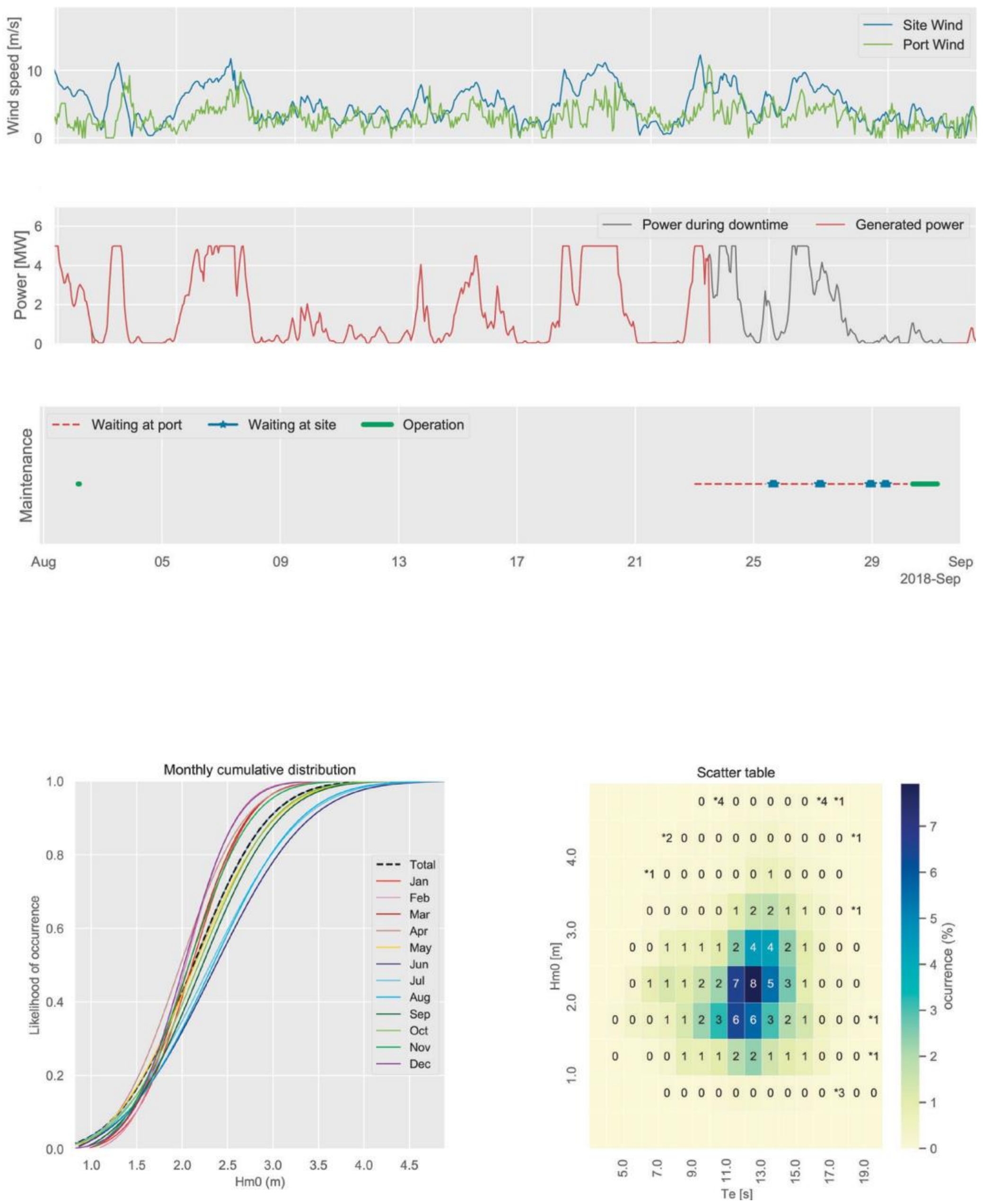

Fig. 9: Example of graphs provided by the Adapt-ORE tool for the assessment of a marine energy project.

5.2 Tank Tests

The Wave & Towing Tank of Universidad Austral de Chile (CEH-UACh) is a highly specialised and unique laboratory in Chile, dedicated to applied research in numerical and experimental hydrodynamics with application to the design and optimisation of ships, response analysis in floating platforms and the study of flow behaviour in submerged systems. The laboratory consists of a tank 45 m long, 3 m wide and 2 m deep, equipped with a unidirectional irregular wave generator, cameras to capture the motions of floating objects, various load and wave height sensors, as well as equipment for the visualisation and analysis of flow characteristics around submerged objects and a towing carriage to tow models along the tank at speeds of up to 5 m/s.

At the CEH-UACh, experiments and analyses using numerical tools have been carried out for the development of hydrodynamic testing capabilities for various types of marine energy conversion systems. These have focused on the response of floating structures to the particular environmental conditions of the Chilean coasts, which are highly energy waves in storm conditions, and specific events, such as the increasingly common occurrence of storm surges, and tsunamis, which marine energy generation systems will have to face. These types of loads, storm surges and tsunamis, have not been widely analysed at a global level, as the current sites of interest and development in Europe, Asia and the United States are not subject to such events, so their study under local conditions presents an opportunity for applied research and a need for developers seeking to install their technologies in the country.

This has involved modernising the laboratory's instrumentation and with it, an emphasis on the training of advanced human capital, both at undergraduate and postgraduate level, with the skills to address the potential development of technologies such as floating wind turbines at local and global level. For this purpose, simple models of marine energy extraction systems have been developed, highlighting a generic floating wind platform that is used for research purposes (Fig. 10).

This experience has involved an accumulation of knowledge from the global review of technologies, the analysis of the capacities installed in Chile for the construction of the systems involved in the platform, and the environmental conditions in which it will have to operate. All this has been reflected in a series of graduate projects both in Chile and Germany [50, 51], presentations at international conferences [52] and scientific publications [53], which lay the foundations for the current projects under development. Among these, a project for the development of a small-scale floating wind platform stands out, which includes the technical and economic analysis of various platform geometries, the development of the basic and detailed engineering and the construction of the first pilot floating wind platform in Chile. Considering that one of the main markets of interest is the aquaculture industry, the project will be installed close to a salmon farm and will be able to provide a significant amount of the required energy.

Fig. 10: Model-scale tests of generic floating wind platform at CEH-UACh.

At CEH-UACh, multiple tests have been carried out using our generic floating wind platform (Fig.10), under different conditions of regular and irregular waves representative of the local conditions in the southern part of the country. The purpose of these tests is to obtain a profile of the hydrodynamic behaviour of the platform considering the mass of the wind turbine in order to focus the analysis on the response of the support platform. Detailed results were published by Hertzsch (2020) [50].

5.3 Numerical Simulations

Using the experimental results and, as a way to extend the analysis to conditions that are complex to represent in the laboratory, a series of numerical simulations have been carried out using Computational Fluid Dynamics, applying both potential codes to determine the response in the frequency domain and viscous codes to study non-linear effects and coupling effects on the systems in the time domain.

The following model (Fig.11) shows the geometry considered in one of the numerical simulations, which replicates the experimental configuration seen previously (Fig.10). While experimentally at the CEH-UACh facilities it is only possible to analyse one effect at a time, i.e. waves or currents, in a virtual tank it is possible to combine the effects of multiple environmental loads providing vital information for the design of floating systems, particularly under typical operating conditions in Chile which consider high wave energy, sustained winds and the eventual presence of multiple users in the installation areas. Likewise, this type of tool allows simulating the interaction between floating bodies, which provides information about the limits within which installation, maintenance and decommissioning activities of the systems would be possible at the end of their life cycle.

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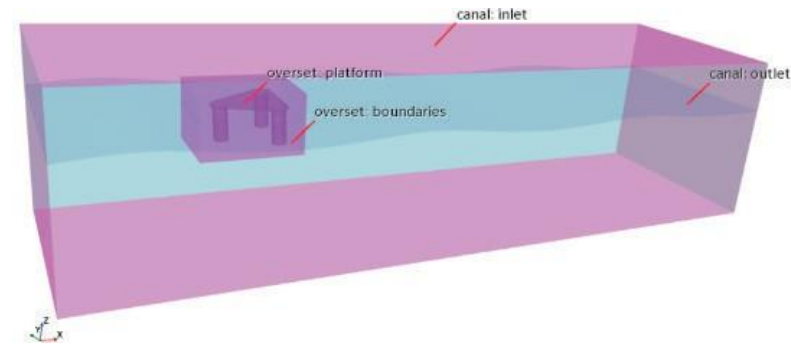


Fig. 11: Example of numerical simulation setup of a generic floating wind platform in waves.

One of the key aspects in the analysis of floating systems is their response to extreme events, since in these conditions the system must be able to stay afloat in its original position, so the prediction of its movements and accelerations is a relevant input for the structural design and in particular for its mooring system. This type of conditions can be estimated in the laboratory, but must be complemented with more complex numerical simulations, which are validated by using experimental results. The study presented in the graphs (Fig. 12) represents the behaviour under a 100 year return period storm. The results obtained by numerical simulations show a satisfactory correlation with the experimental data, thus allowing the extension of the capabilities of analysis of complex systems under wave and current loads, which are of interest to researchers and developers of floating wind power generation technologies.

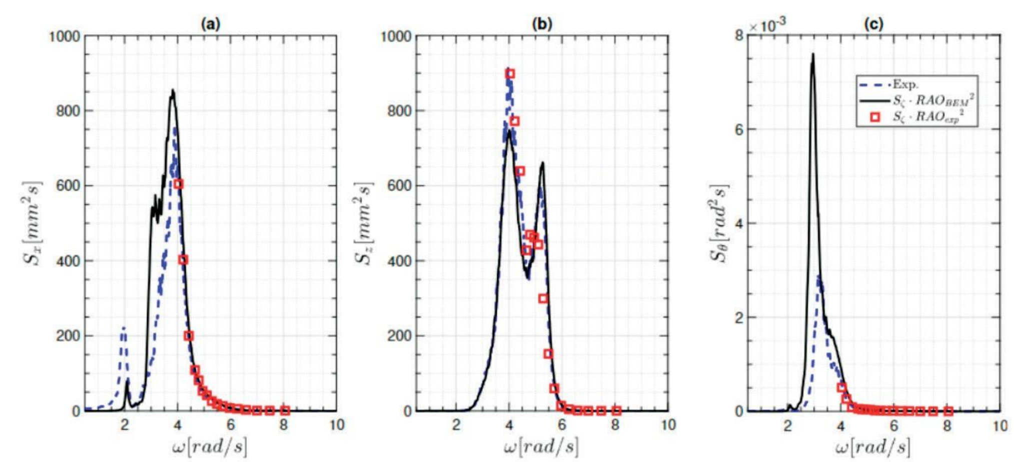
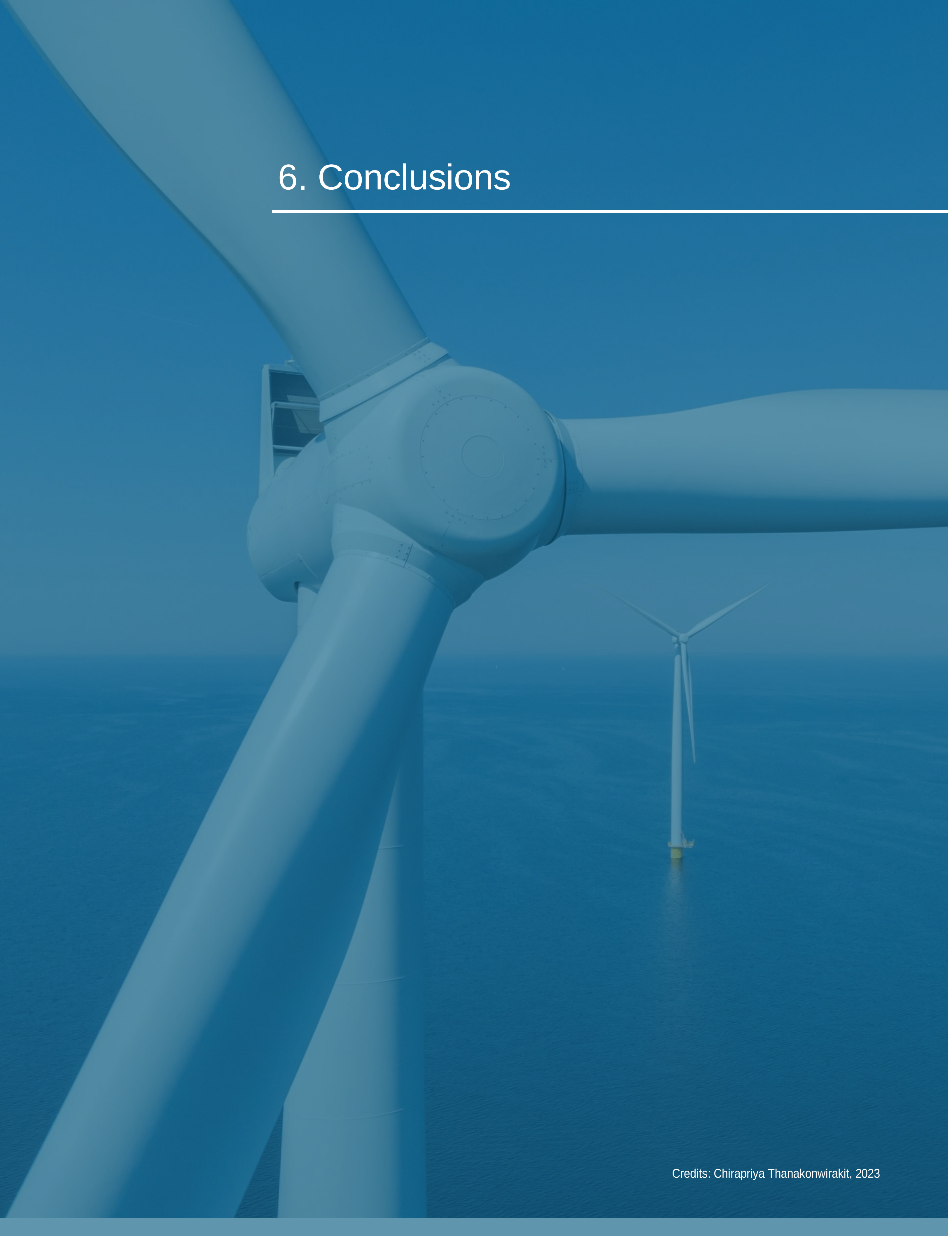


Fig. 12: Surge, heave and pitch response spectra under a 100 year RP condition.

6. Conclusions



Credits: Chirapriya Thanakonwirakit, 2023

The analysis presented here seeks to identify a series of key aspects that could play a key role in the implementation of offshore wind energy projects in Chile, considering local aspects that could be critical and that are not necessarily evident at first sight. Some of the tools and capacities developed by MERIC and Universidad Austral de Chile are also presented, which can to contribute in different areas that have been identified as relevant. Considering the importance of aspects such as the resource, bathymetry, extreme sea and operational conditions, the regulatory framework and the equipment and infrastructure requirements in Chile, potential sites and applications were identified, and recommendations for their development were established.

In particular, the Biobío and Los Ríos regions were identified as having the greatest development potential for offshore wind energy in the medium and long term, respectively. Although technical, environmental and social aspects still need to be studied in greater depth, the development of a national strategy that leads to the development of a high-level technical regulatory framework and territorial planning that includes the Exclusive Economic Zone are the most critical aspects for the development of this energy source in Chile.

Similarly, the use of offshore wind energy in niche markets such as aquaculture and desalination may unlock early experiences with these technologies in the country in the short term, adding the vast potential for the production of green hydrogen in the long term.

Overall, offshore wind energy can make a substantial contribution to meeting the country's decarbonisation goals, reducing pressure on its onshore spaces and taking advantage of its vast Exclusive Economic Zone.

References

1. World Bank. (2019). Going Global: Expanding Offshore Wind to Emerging Markets. Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/716891572457609829/Going-Global-Expanding-Offshore-Wind-To-Emerging-Markets
2. DNV. (2023). Floating Wind: Turning Ambition Into Action. https://www.dnv.com/focus-areas/floating-offshore-wind/floating-wind-turning-ambition-into-action.html
3. World Bank. (2020). Going Global : Expanding Offshore Wind to Emerging Markets (Vol. 33) : Technical Potential for Offshore Wind in Chile – Map (English). Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/954421586853016235/Technical-Potential-for-Offshore-Wind-in-Chile-Map
4. Global Wind Energy Council (2023). Global offshore wind report 2023. Brussels, Belgium. https://gwec.net/gwecs-global-offshore-wind-report-2023/
5. Westwood Global Energy Group (2023). Global Offshore Wind Report. https://www.westwoodenergy.com/
6. The Renewables Consulting Group (2022). Hoja de ruta para el despliegue de la energía eólica costa afuera en Colombia. https://www.minenergia.gov.co/es/micrositios/energ%C3%ADa-e%C3%B3lica-costa-afuera/
7. Tapia, P. (9 de junio de 2023). Energía eólica marina, ¿para cuándo en México?. Forbes. https://www.forbes.com.mx/energia-eolica-marina-para-cuando-en-mexico/
8. Norton Rose Fulbright. (31 de julio de 2023). Global offshore wind: Brazil. https://www.nortonrosefulbright.com/en/knowledge/publications/cb3f61d6/global-offshore-wind-brazil
9. World Bank. (2020). Offshore Wind Technical Potential - Analysis and Maps. https://www.esmap.org/esmap_offshorewind_techpotential_analysis_maps
10. ACERA. (s.f.). Centro de Información. Recuperado el 10 de noviembre de 2023 de https://www.acera.cl/centro-de-informacion/
11. Santana, C. (2014). Energías renovables en Chile: El potencial eólico, solar e hidroeléctrico de Arica a Chiloé. https://biblioteca.digital.gob.cl/handle/123456789/510
12. Mattar, C., & Borvarán, D. (2016). Offshore wind power simulation by using WRF in the central coast of Chile. Renewable energy, 94, 22-31. https://doi.org/10.1016/j.renene.2016.03.005
13. Mattar, C., & Guzmán-Ibarra, M. C. (2017). A techno-economic assessment of offshore wind energy in Chile. Energy, 133, 191-205. https://doi.org/10.1016/j.energy.2017.05.099
14. de Linaje, N. G. A., Mattar, C., & Borvarán, D. (2019). Quantifying the wind energy potential differences using different WRF initial conditions on Mediterranean coast of Chile. Energy, 188, 116027. https://doi.org/10.1016/j.energy.2019.116027
15. Mattar, C., Cabello-Españon, F., & Alonso-de-Linaje, N. G. (2021). Towards a future scenario for offshore wind energy in Chile: breaking the paradigm. Sustainability, 13(13), 7013. https://doi.org/10.3390/su13137013
16. Neira, E., Fuentes, M., Salgado, F., & Jelves, L. (2021, December). Floating Offshore Wind Power: A Case Study for Concepción bay, Chile. In 2021 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON) (pp. 1-6). IEEE. 10.1109/CHILECON54041.2021.9702952
17. Crabtree CJ, Zappalá D, Hogg SI. (2015). Wind energy: UK experiences and offshore operational challenges. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 229(7), 727-746. https://doi.org/10.1177/0957650915597560
18. Dighe, V. V., Pergod, L., y Yung, C. (2022). Offshore Wind Access Report 2022. Tech. Report, TNO. http://resolver.tudelft.nl/uuid:-2ba1f652-080b-4ba7-95e6-8081293c8ad2
19. O'Connor, M., Lewis, T., & Dalton, G. (2013, June). Weather window analysis of Irish and Portuguese wave data with relevance to operations and maintenance of marine renewables. In International Conference on Offshore Mechanics and Arctic Engineering (Vol. 55423, p. V008T09A068). American Society of Mechanical Engineers. 10.1115/OMAE2013-11125
20. Martínez, C., Contreras-López, M., Winckler, P., Hidalgo, H., Godoy, E., & Agredano, R. (2018). Coastal erosion in central Chile: A new hazard?. Ocean & Coastal Management, 156, 141-155. https://doi.org/10.1016/j.ocecoaman.2017.07.011.
21. Campos, R. (2016). Análisis de marejadas históricas y recientes en las costas de Chile. [Tesis de pregrado, Universidad de Valparaíso]. Repositorio Atlas de Oleaje de Chile - Universidad de Valparaíso. https://oleaje.uv.cl/descargas.html
22. Ministerio del Medio Ambiente (2019). Determinación del riesgo de los impactos del Cambio Climático en las costas de Chile (Resumen ejecutivo), Documento preparado por: Winckler, P.; Contreras-López, M.; Vicuña, S.; Larraguibel, C.; Mora, J.; Esparza, C.; Salcedo, J.; Gelcich, S.; Fariña, J. M.; Martínez, C.; Agredano, R.; Melo, O.; Bambach, N.; Morales, D., Marinkovic, C.; Pica, A., Santiago, Chile. https://cambioclimatico.mma.gob.cl/wp-content/uploads/2020/04/2019-09-23-Informe-V00-CCCostas-Resumen-Ejecutivo-Rev1.pdf
23. Winckler Grez, P., Aguirre, C., Farías, L. et al. (2020). Evidence of climate-driven changes on atmospheric, hydrological, and oceanographic variables along the Chilean coastal zone. Climatic Change, 163, 633–652. https://doi.org/10.1007/s10584-020-02805-3
24. Young, I. R. y Ribal, A. (2019). Multiplatform evaluation of global trends in wind speed and wave height. Science, 364,548-552. DOI: 10.1126/science.aav9527
25. Winckler, P., Contreras-López, M., Campos-Caba, R., Beyá, J. F., & Molina, M. (2017). El temporal del 8 de agosto de 2015 en las regiones de Valparaíso y Coquimbo, Chile Central. Latin american journal of aquatic research, 45(4), 622-648. http://dx.doi.org/10.3856/vol45-issue4-fulltext-1
26. GEBCO Compilation Group (2023) GEBCO 2023 Grid (doi:10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b)
27. Díaz-Naveas, J., & Frutos, J. (Eds.). (2010). Geología marina de Chile. Comité Oceanográfico Nacional de Chile. Servicio Hidrográfico y Oceanográfico de la Armada de Chile. http://www.cona.cl/pub/detalle_cientifica.php?pub=1
28. Völker, D., Geersen, J., Contreras-Reyes, E., Sellanes, J., Pantoja, S., Rabbel, W., ... & Weinrebe, W. R. (2014). Morphology and geology of the continental shelf and upper slope of southern Central Chile (33 S–43 S). International Journal of Earth Sciences, 103, 1765-1787. https://link.springer.com/article/10.1007/s00531-012-0795-y
29. Galparsoro, I., Menchaca, I., Garmendia, J. M., Borja, Á., Maldonado, A. D., Iglesias, G., & Bald, J. (2022). Reviewing the ecological impacts of offshore wind farms. npj Ocean Sustainability, 1(1), 1.https://doi.org/10.1038/s44183-022-00003-5
30. Mishima, K., & Mishima, N. (2023). A Study on Visual Impacts of Wind Turbine Arrays in Offshore Wind Farms. In Leveraging Transdisciplinary Engineering in a Changing and Connected World (pp. 132-140). IOS Press. doi: 10.3233/ATDE230605
31. Sullivan, R. G., Kirchler, L. B., Cothren, J., & Winters, S. L. (2013). Offshore wind turbine visibility and visual impact threshold distances. Environmental Practice, 15(1), 33-49. https://doi.org/10.1017/S1466046612000464

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32. Ministerio de Economía, Fomento y Turismo (2014). Guía para la Aplicación de la Ley de Espacios Costeros Marinos para Pueblos Originarios. Santiago, Chile. https://www.subpesca.cl/portal/616/articles-82585_recurso_1.pdf
33. Carrasco-Bahamonde, Daniel. (2022). Espacios Costeros Marinos de los Pueblos Originarios y salmonicultura en Chile. Dilemas en perspectiva histórica. Revista de historia (Concepción), 29(1), 15-45. https://dx.doi.org/10.29393/rh29-2ecdc10002
34. Subpesca (s.f.). Espacios Costeros Marinos de los Pueblos Originarios. IDE Subpesca - Geoportal. Recuperado el 27 de noviembre de 2012 de https://geoportal.subpesca.cl/portal/apps/sites/#/geoportal/pages/asuntos-indigenas
35. Stelzenmüller, V., Gimpel, A., Letschert, J., Kraan, C., & Döring, R. (2020). RESEARCH FOR PECH COMMITTEE: Impact of the use of offshore wind and other marine renewables on European fisheries. https://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2020)652212
36. McMorland, J., Collu, M., McMillan, D., & Carroll, J. (2022). Operation and maintenance for floating wind turbines: A review. Renewable and Sustainable Energy Reviews, 163, 112499. https://doi.org/10.1016/j.rser.2022.112499
37. Det Norske Veritas, "Offshore Standard DNVGL-OS-E301 Position mooring," DNV-GL, 2015. https://doi.org/10.1590/1679-78255692
38. NORSOK. (1997). NORSOK Standard: Marine Operations, Norwegian Standard.
39. DNV. (2018). DNVGL-ST-N001 Marine operations and marine warranty. https://www.dnv.com/oilgas/download/dnv-st-n001-marine-operations-and-marine-warranty.html
40. International Organization for Standardization. (2019). ISO 19901-6:2009, Petroleum and natural gas industries - Specific requirements for offshore structures - Part 6: Marine operations. https://www.iso.org/standard/34591.html
41. Demony, C. (27 de junio de 2023). Exclusive: Brazil aims to pass offshore wind, green hydrogen laws by year-end, energy minister says. REUTERS. https://www.reuters.com/sustainability/climate-energy/brazil-aims-pass-offshore-wind-green-hydrogen-laws-by-year-end-energy-minister-2023-06-27/
42. Naciones Unidas (1987). CONVENCIÓN. DE LAS NACIONES UNIDAS SOBRE EL DERECHO DEL MAR. https://www.un.org/Depts/los/convention_agreements/texts/unclos/convemar_es.pdf
43. Ministerio de Relaciones Exteriores. (2023). PROGRAMA OCEÁNICO NACIONAL "Plan Oceánico Sostenible Chile 2023". Santiago, Chile. https://www.minrel.gob.cl/minrel/site/docs/20230523/20230523111434/programa_oceanico_2023.pdf
44. Neil N. Davis, Jake Badger, Andrea N. Hahmann, Brian O. Hansen, Niels G. Mortensen, Mark Kelly, Xiaoli G. Larsén, Bjarke T. Olsen, Rogier Floors, Gil Lizcano, Pau Casso, Oriol Lacave, Albert Bosch, Ides Bauwens, Oliver James Knight, Albertine Potter van Loon, Rachel Fox, Tigran Parvanyan, Søren Bo Krohn Hansen, Duncan Heathfield, Marko Onninen, Ray Drummond. (2023). The Global Wind Atlas: A high-resolution dataset of climatologies and associated web-based application; Bulletin of the American Meteorological Society, Volume 104: Issue 8, Pages E1507-E1525. DOI: https://doi.org/10.1175/BAMS-D-21-0075.1
45. SPLogistics. (12 de julio de 2022). Los 7 principales puertos marítimos de Chile. https://web.splogistics.com/blog/post/551/los-7-principales-puertos-maritimos-de-chile
46. Coordinador Eléctrico Nacional. (28 de noviembre de 2023). Planificación y Desarrollo. https://www.coordinador.cl/desarrollo/graficos/planificacion-de-la-transmision/demanda-proyectada/
47. Freeman, M. C., Garavelli, L., Wilson, E., Hemer, M., Abundo, M. L., & Travis, L. E. (2022). Offshore aquaculture: a market for ocean renewable energy. Report for Ocean Energy Systems (OES): Lisbon, Portugal. https://www.ocean-energy-systems.org/publications/oes-documents/market-policy-/document/offshore-aquaculture-a-market-for-ocean-renewable-energy./
48. Ibrahim, O. S., Singlitico, A., Proskovics, R., McDonagh, S., Desmond, C., & Murphy, J. D. (2022). Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies. Renewable and Sustainable Energy Reviews, 160, 112310. 10.1016/j.rser.2022.112310
49. Jara, N. (2023). Obtención numérica de límites operacionales mediante uso del open source BEM-solver NEMOH. [Tesis Ingeniería Naval, Universidad Austral de Chile] Repositorio Institucional – Universidad Austral de Chile.
50. Hertzsch, V. (2020). Experimental Analysis of Motions and Loads for a Floating Offshore Wind Platform in Waves [Master of Science, Technische Universität Berlin]. Repositorio Institucional - Technische Universität Berlin.
51 Álvarez, K. Ahumada, J., Cifuentes, C., & Tampier, G. (2023). Análisis numérico de la respuesta hidrodinámica de una plataforma eólica flotante en olas regulares. [Tesis de pregrado, Universidad Austral de Chile]. Repositorio Institucional - Universidad Austral de Chile.
52. Tampier, G. (8-10 de marzo de 2023). Installation and Maintenance of Offshore Renewable Energy Technologies. VIII Congreso Internacional de Diseño e Ingeniería Naval - Colombiamar. Cartagena de Indias, Colombia.
53. Álvarez-Castillo, K., Ahumada, J. M., Cifuentes, C., Tampier, G., & Gallardo, Á. (2023). Numerical analysis of the dynamic behavior of a Floating Wind Platform in regular waves. Ship Science and Technology, 16(32), 43-54. https://doi.org/10.25043/19098642.135