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GEOSCIENCES

A Comprehensive Review of Geophysical Survey Techniques for Offshore Wind Farm Projects

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Abstract: Emissions of greenhouse gases in the atmosphere by burning fossil fuels to generate electric energy has become a major environmental concern. In this scenario, alternative clean sources, such as wind energy, are becoming the top substitute option for supplying electricity and reducing gases emissions. Brazil has huge potential for offshore wind energy. The main challenge, however, is to guarantee the proper installation of these facilities, minimizing risks and ensuring safe operation during its lifetime. To achieve that goal, extensive investigations regarding several geological, engineering and environmental factors must be conducted. Marine geophysical tools have proven to be a reliable, fast and cost-effective way to map the seafloor. This paper provides a review of how different countries are gathering data to map, manage and mitigate seabed features and risks on their offshore wind farm projects. It is shown that, despite many common characteristics, each country has specific rules regarding the survey design. The goal is to provide an overview of the "best practices", and to serve as a baseline for Brazilian regulatory agencies and other stakeholders to design effective hydrographic and geophysical surveys extracting maximum value and knowledge, minimizing geological risks and environmental impacts, keeping cost efficiency for all stakeholders in the operation.

Key words: Bathymetry, Side scan Sonar, High-resolution Seismic, Offshore wind farms, Site Survey.

INTRODUCTION

At the beginning of the industrial revolution, humanity began to burn fossil fuels to generate energy for the development of civilizations. The continuous use of that source of energy has resulted in the release of an immense amount of potentially harmful gases into the Earth's atmosphere, mostly carbon dioxide and methane. Over the years these gases have been accumulating in the atmosphere and today they represent the most critical impact factor on the planet's climate, becoming a major threat to the stability of ecosystem services, human well-being, and sustainable economic development (Wang et al. 2019). As society's environmental concern regarding the impacts of generating energy by burning fossil fuels increases, both globally and locally, alternative clean energy sources are becoming the top choice for expanding electricity generation capacity. Among many, wind energy is today the most well-established and economically relevant.

The use of wind to generate energy dates back from 200 BC, as wind-powered machines were used to pump water, grind grains and salt making at the Persian-Afghan borders (Kaldellis & Zafirakis 2011). Today wind energy is being widely used to supply the electricity needs of modern society all over the world, but especially in China, Europe and USA, both in land and at sea (GWEC 2019).

Offshore wind energy is the generation of electricity through the installation of a series of turbines spread out over shallow (between 15 and 40 meters) oceanic areas, not too far from the coast, known as Offshore Wind Farms (OWF).

In the year 2019, only 4.3% of the planet's total energy was generated through wind energy, from which only 0.2% was generated offshore. However, the New York State Energy Research and Development Authority (NYSERDA) estimates that the state alone has the capacity to generate up to 39,000 megawatts (MW) of offshore wind energy, which corresponds to 15 million households supplied exclusively with clean and renewable energy. Det Norsk Veritas, one of the world's largest classification societies of companies in the energy sector, states in its 2019 report that around 30% of all energy on the planet will be generated by wind energy by the year 2050, with 12 % of this energy generated offshore and 18% generated onshore (DNV GL 2019).

Brazil has great potential for wind energy production. In 2018, the Brazilian Energy Research Office (EPE in its Portuguese acronym), a public company linked to the Ministry of Mines and Energy, carried out the first studies on the offshore wind potential within the scope of the National Energy Plan 2050 (PNE 2050) and reached an estimate of 1,780 GW for the Exclusive Economic Zone (EEZ) (EPE 2019). This potential, despite being significant along the entire Brazilian coast, shows greater potential on the coasts of the states of Rio Grande do Norte, Ceará, Rio de Janeiro, Espírito Santo, Santa Catarina and Rio Grande do Sul (Figure 1). The report also estimates that the potential of the new offshore areas in licensing process at IBAMA would be around 106.4 GW.

The main challenges in the development of an offshore wind farm rely on its installation and reliable operation (Perveen et al. 2014). Besides the generators, there are several other facilities needed to capture the energy, transform it into electricity and transport it to onshore (Thomsen 2012). The wind turbines capture the wind's energy and generate electricity, which flows through a series of buried cables to an offshore substation where it is collected, stabilized, and prepared to be transmitted to another substation onshore. From there the energy is supplied to an existing network on the continent to be delivered to the final consumers (Figure 2).

To guarantee the proper installation of these facilities, minimizing environmental and social impacts and ensuring a safe operation during its lifetime, many years of detailed investigations are necessary. These investigations focus on different factors: existing navigation routes in the area, seafloor geology and geotechnics (limited to the upper 100m below the seafloor), habitat mapping, migration routes of birds and aquatic mammals, sediment mobility and coastal dynamics, as well as the social impacts on the communities located nearby the installation site. Moreover, there are several legal requirements and environmental approvals which are required, and many depend on the results of these investigations. Uncertainty in physical conditions increases development risk and, by extension, offtake project's cost (Reynolds et al. 2017a).

Marine geophysical tools have proven to be a reliable, fast and cost-effective way to map the seafloor. They have been successfully used over the last 70 years in geological, geotechnical and environmental investigation for all kinds of subsea engineering projects. The investigations needed on offshore wind farm construction sites demand basically the same approach as used on site surveys for the oil industry. However, the need for more robust ground models makes the conventional approach of site surveys, in which geophysical data interpretation is conducted

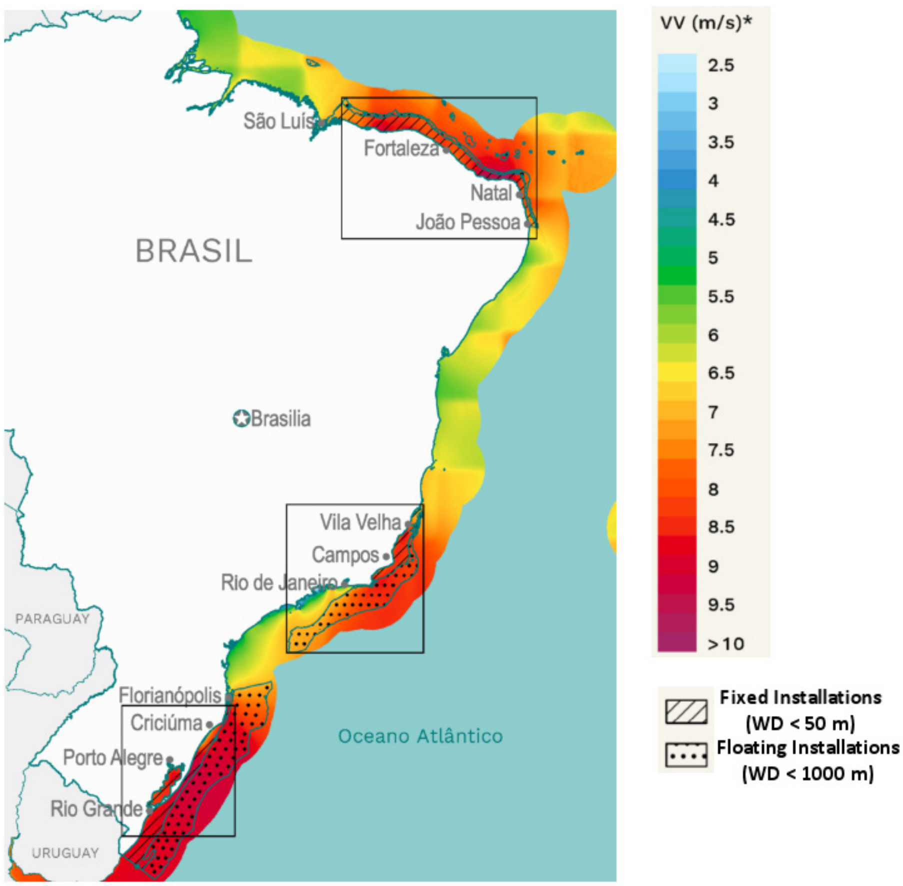

Figure 1. Wind speed (WS) and potential areas for wind energy Generation along the Brazilian continental margin. (Modified from https://dialogochino.net/pt-br/mudanca-climatica-e-energia-pt-br/56207-os-parques-eolicos-offshore-sao-o-futuro-da-energia-na-america-latina/ - Consulted on May 27, 2024).

without recourse of geotechnical information obsolete. This paper is a review about how geophysical tools have been used in different countries of the world regarding the geological investigation of the seabed for the installation of offshore windfarm.

Construction stages of an offshore wind farm

In general, the construction of an offshore windfarm is divided into five stages: (i) Development (or Preliminary); (ii) Construction (or Project); (iii) Execution; (iv) Operation and Monitoring; (v) Decommissioning (Reynolds et al. 2017a, b, Wood & Knight 2013, BOEM 2020, Fischer et al. 2020, Fugro 2017, OWPB 2015). For each of these stages there are specific investigations that must be conducted to progressively evaluate the geological, geotechnical and environmental conditions of the seabed at the construction site. The rules for these investigations change from country to country.

The Development phase consists of the preliminary investigation to assist decisions making about whether the general geological conditions at the location of the planned offshore facilities are consistent with the foundation type (Figure 3) and the construction process and what measurements are important for site investigations. In the United States documentation about the decommissioning and site clearance plans must be already included in this phase (BOEM 2015). More specifically the following studies must be conducted in this phase:

- Desktop geological study.
- Construction of the initial geological model.

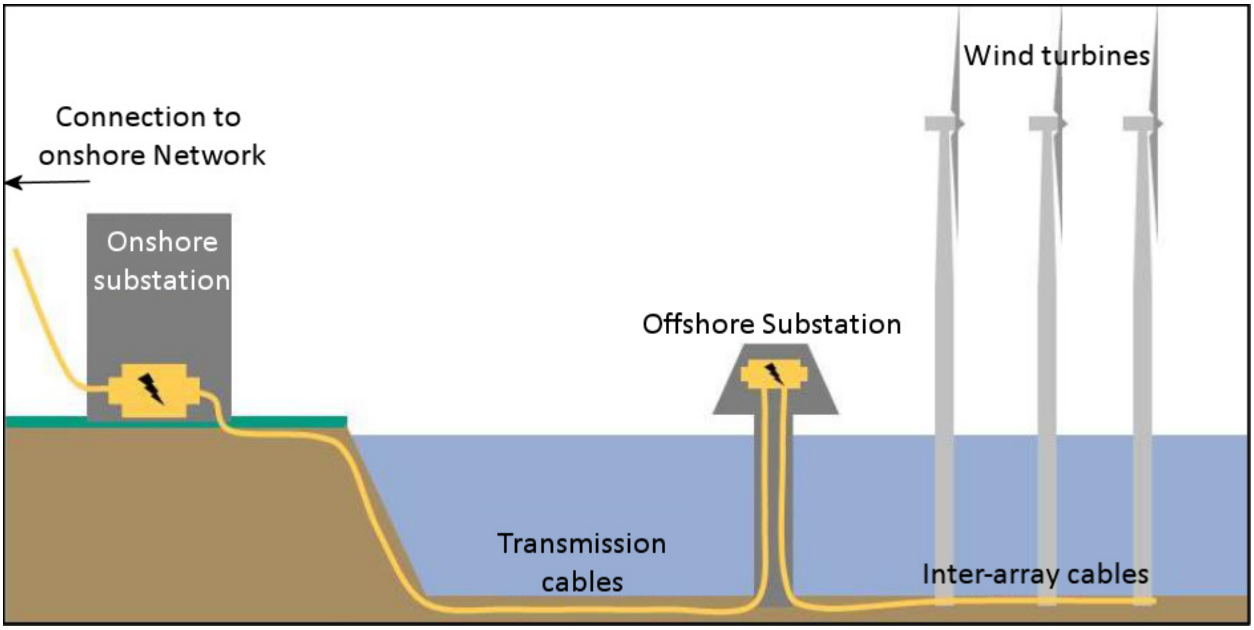

Figure 2. Schematic overview of an offshore wind farm installation (Modified from OWPB 2015).

- Preliminary geophysical and geotechnical reconnaissance.

During the construction phase the choice of the best geophysical and geotechnical investigation methods are determined by the type, size and importance of the generators and substation, by the uniformity of the terrain conditions, by the morphology of the seabed and existing types of sediment. The area under investigation must also consider possible deviations from the plan regarding the location of the structures. Before initiation of this phase, the following studies must be conducted:

- Detailed geophysical and geotechnical survey;
- Identification of the main geotechnical hazards;
- Establishment of the stratigraphic and geological models of the site;
- Definition of the geotechnical parameters for pre-dimensioning the foundations of each geological province;
- Preliminary characterization of cable routing, installation, and requirements for defining the trenching method – Ploughing, Cutting or Jetting (Figure 4).

The Execution phase is essentially an engineering phase and does not involve geophysical surveys. This phase is focused on the production of the foundation elements, followed by the monitoring of the seabed's conditions, the development of excess interstitial pressure in the supporting part of the foundation and of the subsidence and inclination of the foundation body. During this phase investigations to evaluate potential mobility of the seabed sediments to protect the system against scouring of the bottom are undertaken.

Activities during the Operation and Inspection phase consist of monitoring the structural behavior of the facilities (wind generators and substations) under workloads due to weather conditions (wind and wave), and of the seabed's sediment dynamics in the passageways of the cables inside and outside the wind farm to avoid accidents due to transmission cables coming out of the ground.

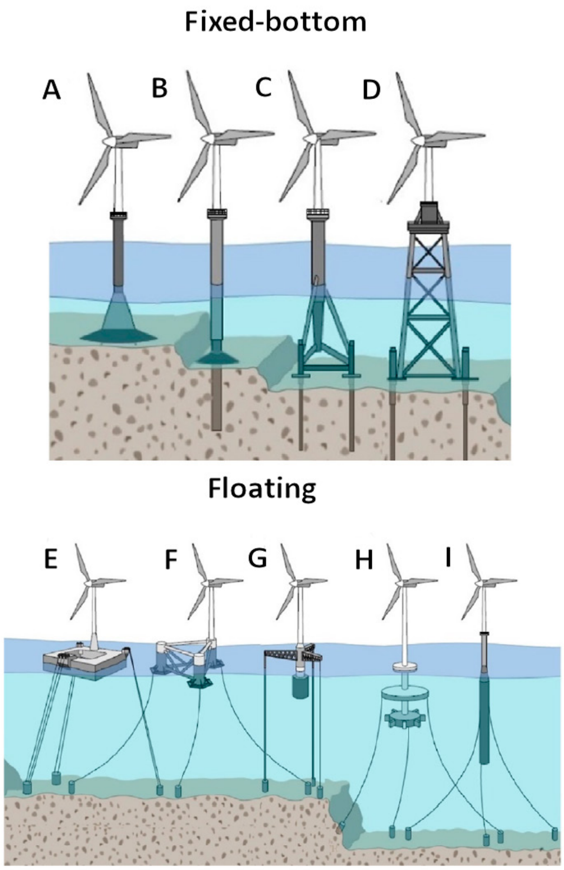

Figure 3. Examples of offshore wind turbine generator's foundation structures (Modified from Ma et al. 2024).

The Decommissioning phase occurs when an offshore wind farm reaches the end of its useful life. Given today's wind turbine service life of 20 years (Topham et al. 2019, Smith & Lamont 2017, Irawan et al. 2019), there is an urgent need to thoroughly prepare for the different possible end-of-life scenarios. The decommissioning process is generally the installation process in reverse, involving offshore dismantling of the major elements and onshore disassembly of sub-components. However, as the amount of decommissioned wind farms are so far very limited, the lack of experience poses as the main challenge (Ortegon et al. 2013). Topham et al. (2019) described some challenges in the decommissioning of offshore wind farms. First, the regulatory framework. The decommissioning process for the whole offshore industry lacks relevant guidelines for recommended practices. Most of the current practices are too vague and mainly based on the decommissioning experience of oil and gas facilities. This occurs due to some clear synergies encountered in the process, but some procedures do not totally comply to renewable energy. The second is the planning and costs of the decommissioning process. The authors state that it is very important that the decommissioning procedures should be planned during the design phase of a project and as part of the whole-life costing exercises. The third is the definition of when the decommissioning will happen. Because the decommissioning plans must be delivered in the initial phase of the project, substantial technical advances, as well as environmental demands, regarding the feasibility of the whole operation may arise within that timeframe, which may impact the original plan (for better or for worse).

And there is more. Smyth et al. (2015) discuss the environmental and economic benefits of a partial removal (instead of a total removal) of the structures when the decommissioning phase has arrived, given that complete removal can damage the seabed, the habitat and the new equilibrium which has been created. This approach has been introduced by the US National Fishing Enhancement Act of 1984 (Kaiser 2006). Leaving the structures that after the 20-30 years of operation serve as artificial reef, may bring benefits for commercial and recreational fishing plus cost reduction for developers. On the other hand, the partial removal of the structures may pose some issues related to safety of navigation, liability of the reef and the potential for spread of non-indigenous species.

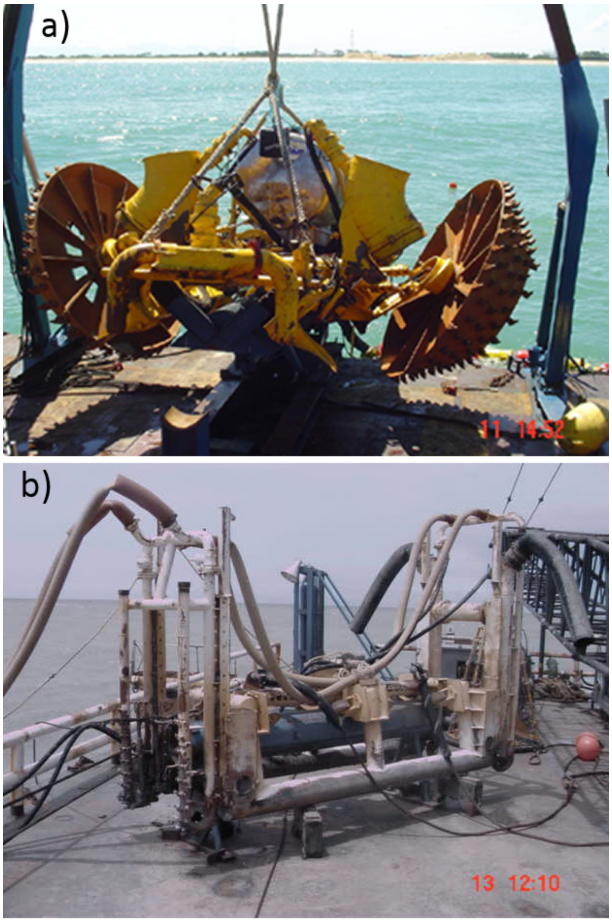

Figure 4. Cable trenching Machines: a) Cutting (suited to rigid seabed or stiff clays); b) Jetting (effective in sandy sediments). Source: Authors.

Environmental aspects of the offshore wind farms

While the range of potential ecological risks from onshore wind farms to wildlife and habitats is relatively well documented, the direct and indirect effects on the environment of developing offshore wind farms are still unclear (Inger et al. 2009). The development of offshore wind farms is challenged by concerns from all stakeholders about the potential effects on the environment, specifically regarding birds and marine mammals, and the habitats that support them. Moreover, the socioeconomic impacts on fishing communities close to operation sites, as well as on aesthetics, historic sites, recreation, and tourism must be considered. However, up to now there are no systematic and/or widely accepted methodology to evaluate the potential damage to wildlife, habitats and communities, leaving developers and regulators in an uncertain position (Copping et al. 2020).

The level of environmental impact depends on the stage of the project (development, construction, execution, operation and monitoring; decommissioning). The greatest impacts are expected during the construction, execution and decommissioning stages (Inger et al. 2009), when more invasive operations such as excavations for the trenching and recovering of the transmission cables and installation/deinstallation of the generators take place.

The impacts include bird strikes (Brabant et al. 2015); disruption of marine mammal corridors, as well as damage to fish and sea turtles due to the construction of bottom-mounted turbine towers (Lovich & Ennen 2013, Tomsen et al. 2006); the potential for erosion and sediment resuspension around bottom-mounted wind turbine foundations (Baeye & Fettweis 2015); displacement or barrier effects due to the presence of large offshore wind farms (Vallejo et al. 2017); and disconnection of ecological environment such as roosting and feeding sites (Perveen et al. 2014). On the other hand, studies in the Block Island Wind Farm, in the east coast of the United States, showed that the presence of the fixed installation favored the colonization of several kinds of animals (Hutchison et al. 2020). It was observed that after four years of operation the fauna associated with the jackets were dominated by filter- feeding mussels and associated epibionts. Mussel aggregations dominated the footprint of the jacket structures. Predators such as sea stars, moon snails, and crabs, as well as numerous fish had become attracted to the structure and associated epifauna.

In Brazil, there is still no clear definition about which criteria should be considered when assessing the environmental impact of an offshore wind farm. IBAMA (2019), in its report "Mapping of environmental decision-making models applied in Europe for offshore wind projects" compiles the licensing demands from 6 European countries (Germany, Belgium, Denmark, Spain, France and Portugal). The objective was to gather technical and scientific elements to support a safe and transparent environmental regulatory model for future investments in offshore wind generation. Lima (2021) presents a proposal for an environmental impact management program for offshore wind farms in Brazil, indicating basic guidelines to be followed regarding biodiversity, habitats, flora and fauna; Geology and sedimentary coverage; landscape; aquatic environment; air quality; climatic factors; population and human health; cultural heritage and other users of the sea, according to the project stages. In some countries like United Kingdom, Germany and Denmark, these studies are conducted by governmental agencies with the support of research institutes and universities. In the oil industry, which is used as reference for many issues regarding offshore wind farms, environmental studies are often conducted by private companies. They are also responsible for providing the study's final reports, which frequently are questioned by environmental agencies responsible for issuing the required licenses. After analyzing the management actions taken to protect wildlife and habitat in 10 offshore wind farm projects around the world, Copping et al. (2020) concluded that the environmental regulatory requirements in many cases are not sustained by scientific questions, which gives space to considerable discussions about the real deleterious impacts of the venture. The weak understand and the uncertainty generated by the collection of limited or unreliable data, may result in more restrictive regulations and more expensive interventions that may be counterproductive, not solve the problem they were intendent to correct or even create other unexpected hazards (Ricci & Sheng 2013).

Marine geophysical methods

It is not scope of that article to go into details of the marine geophysical methods. There are several publications (scientific papers and books) where specific aspects of each method are described (Ayres Neto et al. 2023, Blondel 2009, 2012, Mohammadloo et al. 2019, Kristensen 2016, Plant et al. 2002, Wölfl et al. 2019, Meng et al. 2023, Nian et al. 2021, Collier & Brown 2005, and many others). Here, a quick and objective summary of the main methods will be presented.

The main geophysical techniques used to survey the seafloor are generally classified as active sonars, which are based on the transmission, reflection, and reception of acoustic pulses emitted by a controlled source. They operate in a wide range of frequencies, from 500 Hz to 500 kHz, depending on the utility and water depth. There are three methods: Bathymetry, side scan sonar and high-resolution single channel seismic (also known as sub-bottom profiler).

Bathymetry is used to map the depths, slope and shape of the seafloor, that is, its morphology. Echosounders measure the time lapse between transmission and reception of the acoustic pulse, and by knowing the sound speed in seawater, it calculates the local depth (Figure 5a). The acquisition and processing procedures are very complex and several factors (seawater speed, tides, ship's attitude, sensor alignment, weather condition) much be considered to ensure good data quality. Today, multibeam echosounders also return the intensity of the returned signal (backscatter),

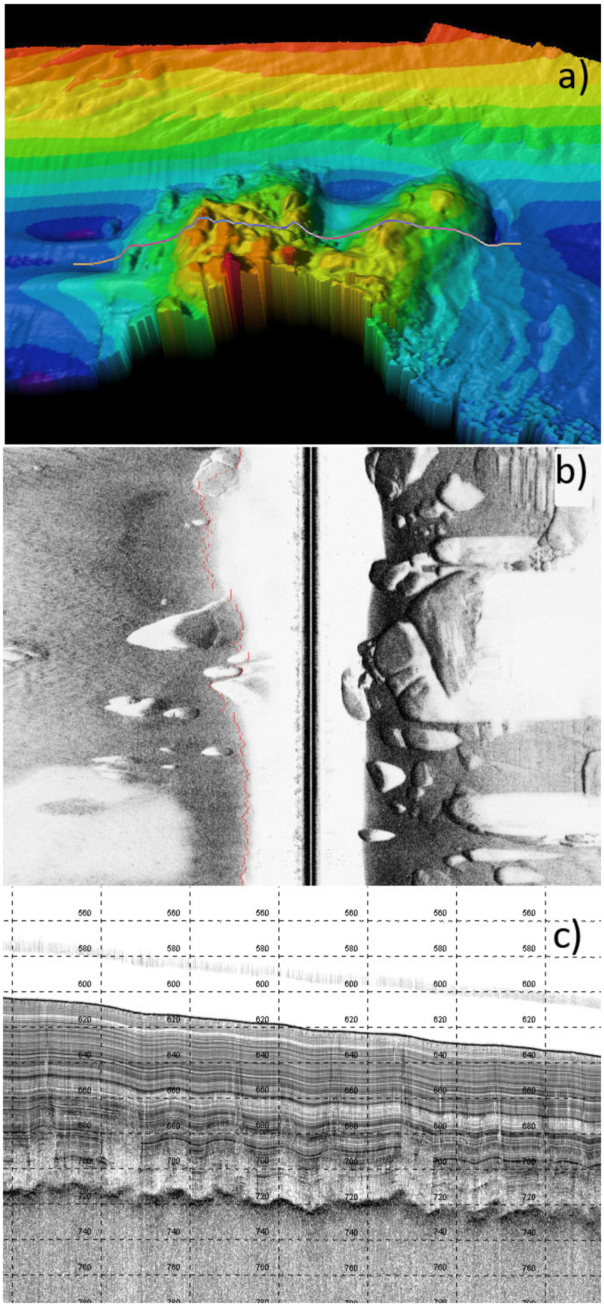

Figure 5. Examples of a) bathymetric, b) sonographic and c) seismic data.

which is proportional to the sediment's reflection coefficient. This information allows to generate a mosaic where different backscatter intensities are related to different kinds of sediments.

Side scan sonar is an equipment able to image the seafloor by emitting two side looking pulses covering a wide area of the seafloor. These systems deliver a sonographic mosaic, very similar to the backscatter mosaic, but with higher resolution. The sonographic patterns are described in terms of intensity and texture, which in turn, are related to the geology of the seafloor (Figure 5b). The width and resolution of the image depends on the frequency of the emitted signal. Low frequency signals (~100 kHz) may cover a corridor up to 1000 m wide with a resolution of 4-5 meters; high-frequency systems (> 500 kHz), on the other hand, are limited to swaths of less than 100 m, but deliver images with centimetric resolution. Sonographic surveys are also very useful for subsea archaeological investigation.

Seismic methods can be separated into two groups according to their sources: resonant Sub-bottom Profilers and impulsive Sparker and Boomer. Sub-bottom profilers are systems used to map the geological layers below the seafloor and operate within a frequency range usually below 6 kHz (but may be up to 20 kHz). This system has the ability to penetrate the seafloor up to 80 m, depending on the geological characteristics of the seafloor, with a vertical resolution of 0.5 m. They are very useful in mapping the upper 10-20 meters of the sedimentary column, showing the structural disposition of the subsurface layers, the presence of geological faults and shallow methane pockets. They are, however, very sensitive to the geology of the seafloor, being more effective in muddier, low reflective sediments. Sandy sediments present higher acoustic impedance and investigation depth is very restricted (in some cases close to zero). Boomers and Sparkers generate signals in a frequency range between 400 Hz and 2 kHz. These are much powerful sources generating stronger signals that are able to travel deeper down (up to 300 m) in the sediment column. However, due to their lower frequency content, in general they offer a data with lower vertical resolution (Figure 5c).

It is important to highlight that geophysical methods are indirect methods. They are not able to give precise information about the geological characteristics of the seafloor, but only to indicate existence of “different materials” or “anomalies”. Geological and geotechnical samples are necessary to tide the geophysical information with geological information. However, because these tools are very efficient, non-invasive and cost effective to survey large underwater areas, they strongly reduce the amount of samples, by allowing the selection of strategical locations, with huge implications on the overall project’s budget.

A fourth method that is sometimes (as we will see in the next section) demanded in site surveys for offshore wind farms is magnetometry. This technique measures small deviations of the total magnetic field and is used to identify the presence of shipwrecks, submarine pipelines, unexploded ordnance device (UXO), as well as any other metallic debris which may represent any danger to the engineering activity.

General geophysical procedures demanded for offshore wind farms

A strong knowledge of seabed and sub-seabed geological conditions is critical to ensure that offshore wind installations operate safely and efficiently during its whole life cycle. The approach to offshore site surveys that has been used for the last decades consists of undertaking geophysical, geotechnical, environmental and, eventually, archaeological surveys separately. And there are good reasons for that. By being faster and relatively cheaper, the geophysical survey provides results to advantageously select optimal locations for geotechnical and geological sampling. Simultaneous geophysical and geotechnical campaigns may not give that possibility, unless enough resources from both sides are available to allow near real time geophysical data to be processed and interpreted, constantly feeding the geotechnical team with information regarding coring location (Fugro 2017). Similarly, the geophysical information can provide the personal responsible for the environmental and archaeological survey a general overview of the area, in which a plan for more detailed investigation can be devised. On the other hand, the advantage of conducting simultaneous geophysical, geotechnical, environmental and archaeological surveys, is that all the information needed for the project will be collected in much less time, helping expedite the overall wind farm development process. The factors to consider when choosing the survey approach are related to weather window, geological complexity of the area and ship availability.

Despite the different regulatory frameworks in each individual country, basically the same investigations are required for an offshore wind farm site survey (Figure 6). Due to similarities with the processes involved, many procedures are adapted from the offshore oil and gas industry. However, depending on the risks associated to each particular geological environment, some procedures have to be totally reviewed.

This section will outline the most relevant technical specification for geophysical investigations which some countries demand for the project developer (Reynolds et al 2017a, b, Wood & Knight 2013, BOEM 2020, Fischer et al. 2020, Fugro 2017, OWPB 2015). These specifications may be different according to the stage of the project.

Denmark

Within the governmental tendering process, the Danish Energy Agency (ENS) selects a site for which interested developers can apply. A previous geophysical and geotechnical survey is carried out in advance and made available

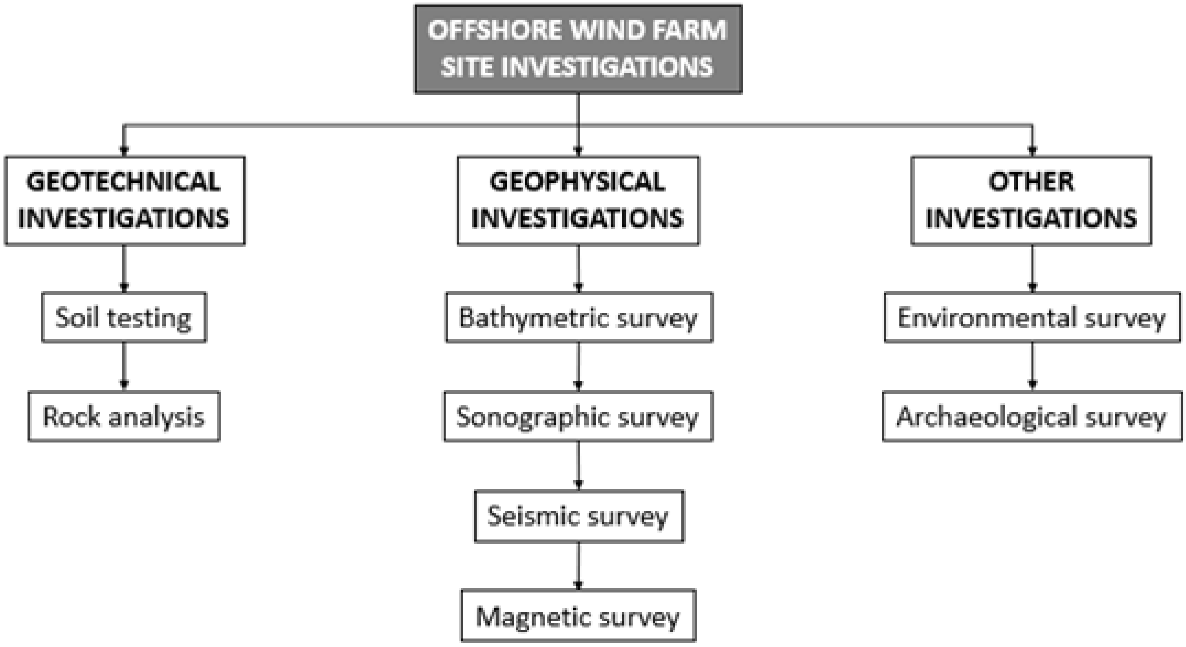

Figure 6. Basic survey types required for offshore site investigation.

for tenders (Fischer et al. 2020). This preliminary survey is used to delineate preliminary site selection and decision making where to locate the structures (including substations, wind turbines and cables), assess the general feasibility of the use of jack-up platforms and anchor-based vessels during the investigation and construction phases, determine general requirements for foundation concepts, design and construction, and conduct environmental impact assessment (EIA), including marine archaeological conditions. (Energinet 2013a).

For the next phases the ENS specifications for geophysical surveys include (Energinet 2013b):

- Detailed mapping of the surface of the seabed including objects of biological and archaeological relevance, man-made objects, natural seabed features and geohazards.
- Geophysical investigations in the wind farm area to set up a preliminary three-dimensional geological model to a minimum depth of 100 meters below seabed.

The objective of the geophysical survey is to obtain adequate information to establish a geological understanding of the area, providing input to environmental, archaeological and UXO evaluations and subsequent geotechnical campaigns. Furthermore, it also provides data to assist in planning the inter-array and transmission cable routes. To achieve that requirements the minimum survey specifications are as follows (Fischer et al. 2020):

- Maximum horizontal positioning accuracy tolerance of 0.5 m and 2.5 m for hull-mounted and towed systems, respectively.
- Full coverage by multibeam echosounder to a resolution of Order 1A of IHO (2024).
- Dual frequency, full coverage, with 200% overlap side scan sonar mapping of the area to detect objects larger than 0.5 m.
- High-frequency sub-bottom profiler on every 100 m spaced line (10 m signal penetration).

- Sparker/Boomer survey every two lines (60 m signal penetration)
- Ultra-high resolution seismic survey every other second line (100 m signal penetration)
- Magnetometer (gradiometer) survey in every line.

The deliverables consist of a bathymetric contour map, a detailed terrain model (0.25 m spatial resolution), map of surface geology, maps of man-made objects, maps of sub-seabed layers, isopach map of main geological layers, 3D geological model, a map of magnetic anomalies classified as natural or anthropogenic, an overview of boreholes and CPT location based on the preliminary farm layout and provisional foundation design.

France

In France, up to 2020, no mandatory requirements about the site investigation for offshore wind farms were defined by the authorities, mainly because approval procedures are still pending (Fischer et al. 2020). However, special guidance on site geophysical and geotechnical investigation for offshore wind farms are already developed from a technical point of view. Here the specifications for site investigation have increasing degree of detail according to the stage of the project.

During the development stage the aim of the geophysical survey is to identify the major geological and geotechnical hazards, to define the seabed's morphology, geology and stratigraphy, to stablish the pre-dimensioning of the foundations and to provide a preliminary characterization of the seabed along the cable routes. To accomplish that task recommended survey specification must consider (Fischer et al. 2020):

- Full field multibeam coverage with 50% to 100% overlap. Backscatter processing is recommended.
- Dual frequency sonographic survey covering 100% of the wind farm area with a 50% to 100% overlap. Grab or gravity-core samples must be collected to calibrate the side scan reflection patterns.
- High-resolution seismic (SBP or Pinger) survey for shallow penetrations with vertical resolution of 30 cm. Line spacing should be 250 m with cross lines every 1000 m and along all cable routes.
- Boomer or Sparker, single or multichannel survey for penetrations between 50 and 100 m with vertical resolution of less than 1 m. Line spacing should be 250 m with cross lines every 1000 m.

For the construction stage survey specifications are more restricted. Now, the objective of the survey is to identify all geological risks, to define the stratigraphic profile and correlate with the geotechnics for the dimensioning of the foundations and to the burial conditions of the cables. The recommended extent of the main geophysical survey is:

- For the seafloor topography a full coverage multibeam bathymetry with 100% overlap of all foundation location (wind turbines, meteorological mast, transformer substations and cables).
- Side Scan Sonar (dual frequency) survey covering the location of each structure with 100% overlap. Mosaic resolution depends on the type of structure (wind turbines, meteorological mast, transformer substations and cables).
- Single and multi-channel reflection seismic using boomer or sparker source in a grid with two perpendicular lines at the location of each structure.

- A refraction seismic survey to determine the compression wave speed (Vp) at all structure locations and cable routes. Penetration between 5 m and 20 m depending on the objectives.
- Determination of the shear wave speed (Vs) dragged on the seabed or towed just above the seabed obtained by combined seismic refraction and MASW (Multichannel Analysis of Seismic Waves) so to collect as much information as possible in the first 2 to 3 meters below the sea floor.
- Thermal conductivity measurements using in-situ techniques (probe installed by penetration) or in laboratory samples up to 2 to 3 meters, depending on the planned burial depth.

Here the deliverables are not clearly specified.

Germany

In the German Exclusive Economic Zone, the procedures for the site investigations are defined and regulated by the Standard Ground Investigations of the German Hydrographic Agency (BSH 2014) that has been elaborated by an expert group on behalf of the BSH. This document defines a stepwise procedure for the site investigation that must be carried out in parallel to different project development phases. The geological/geophysical survey conducted on the development stage of the project consists of the investigation of the area for the preliminary planning of the location of the structures. The information will assist in decision making about whether the planned offshore structures can be built in relation to the seabed conditions. For the construction stage, the scope of investigations is determined by the type, size and importance of the construction of wind farms/substations, by the complexity of the seabed morphology and geology, as well as the layers below the seafloor. During the Operation and Monitoring stages, surveys must be conducted to verify the action of bottom currents on the seabed sediments and the existence of scouring processes.

According to BSH (2014, 2019) the geophysical survey must be conducted based on the following standard:

- Positioning accuracy must be better than 5 m ± 5% of the mean water depth and cruising speeds must be 4 knots maximum (provided that the equipment used does not demonstrably allow for higher cruising speeds). The allowable lateral deviation of the predefined survey lines is limited to 10 m.
- A full coverage multibeam bathymetric survey with accuracy compatible with IHO (2024) order 1B. This survey must be repeated once a year after the operation is initiated. The accuracy of these monitoring bathymetric surveys must be in accordance with IHO order 1A survey.
- The sonographic survey (side scan sonar) must be executed using a frequency of 100 kHz or higher. It must guarantee 100% coverage of the area and be able to identify objects bigger than 1 m on the seafloor. Positioning accuracy of the equipment must be better than 10 m. This survey must be repeated during the monitoring phase to detect erosion areas, scour or obstacles. Reflection patterns must be calibrated by means of ground truthing.
- High-resolution 500 m grid spacing seismic survey using Boomers or alternative sources with comparable or better performance and sufficient signal penetration, resolution of at least 1 m required close to the surface. Supplementary sub-bottom profilers or

chirp sonar for areas close to the surface (e.g. along the planned cable routes), vertical resolution of at least 0.5 m. Above sea state 4, a motion sensor must be connected to the system. This survey is to be conducted only in the first stage of the project.

- If the occurrence of wrecks, cables or UXO is indicated either by desktop studies or sonographic and seismic surveys, a magnetic survey with a gradiometer must be conducted. Line spacing shall correspond to the seismic profile grid or covering the whole area if necessary. Resolution of the anomalies must be 0.1 nT. The altitude of the magnetometer over the ground should be chosen depending on the geophysical study findings. If ordnance is suspected, then lower than 4 m.

Deliverables are the Bathymetric map of the survey area, the digital SSS mosaic with horizontal resolution of 0.5 m and a corresponding map with the superficial distribution of sediments. Seismic data must be presented in geological longitudinal sections and transects and with a map with the location of geological units and structural elements. The findings of the magnetic survey must be displayed on a map, together with a list of all anomalies discovered, including comparison with the findings of SSS investigations.

All findings of geophysical investigation are to be compiled together and assessed in a geological report. The report provides a basis for further planning and contains a description of the geological model upon which the structures should be constructed. It should be set up from an engineering geological point of view and should, together with geotechnical documents, serve as empirical evidence for validation of the planned sites and for selection of suitable foundation types.

The Netherlands

A developer with the intention to build an offshore wind farm within the Dutch territorial waters is provided by the government with preliminary desktop studies regarding several information about the area (RVO 2018a). This report consists of archaeological, geological, geophysical, geotechnical, morphodynamics, and metocean information available for the selected area. This report will be the basis for the developer to plan the detailed investigations needed for the development of the wind farm. However, they must conduct a complementary geophysical and geotechnical survey in order to fill the gaps in the previously provided information. According to RVO (2018b) the objectives of this detailed geophysical survey are to obtain data for the wind farm development, in particular but not limited to the foundation design and the cable burial; determine the accurate sea floor elevation; provide information about natural and man-made seabed features, UXO and other obstacles; provide geological interpretation of the seabed, locate structural complexities or geohazards (shallow gas, channels, faulting); and provide input for the specification of the geotechnical sampling and testing.

The Netherlands holds no specific scope for site investigation for offshore wind farms but recommends that geophysical survey shall comply with acknowledged standards such as The Dutch Standard for Hydrographic Surveys (which is basically the IHO standard) for multibeam echosounder acquisition, and the SEG-y rev. 1 for trace headers for seismic data (Fischer et al. 2020). Despite regulatory agencies determine no specific indication of the survey procedures, RVO (2018b) outlines an example of the specifications for a geophysical site executed for the Hollandse Kust (zuid) WFS III and IV projects, located in water depths ranging from 18 m to 28 m, which consisted of:

- Full coverage multibeam survey in a grid of 100-meter spaced lines, with cross lines every 750 meters, using an equipment which can (theoretically) generate beams of 0.1° x 0.5°, resulting in a DTM resolution capable of detecting targets of 0,5 m in size.
- A dual frequency (100/600 kHz) side scan sonar survey, following the same bathymetric grid generating a mosaic with a minimum lateral resolution of 0.2 m.
- A sub-bottom profiler survey with acoustic penetration to about 10 ms (limited to local geological constraints) below seabed and vertical resolution is estimated as 0.1 m. The seismic survey grid was configured to main lines spaced by 300m and cross lines every 750 m.
- A single-channel seismic survey using a 100-tip sparker source with vertical resolution is estimated at 0.5 m.
- A multi-channel seismic survey using a 540-tip dual-frequency sparker with a vertical resolution estimated from 0.5 m for the upper layers to 0.9 m in the deeper layers.

In another project, the Gemini Windpark, a complementary 3D ultra-high resolution seismic survey was conducted. The goal was to identify significant stratigraphic and lithological horizons that characterize the site, as well as subsurface structures that may represent changes in material properties relevant to the design (Geosurveys 2020).

The deliverables were track plots, bathymetry, seafloor sediment classification, contacts, and geohazards maps, geological charts and profiles for the sub-seabed geology. Accompanying a geological ground model including stratigraphy, lateral sediment variability, geohazards, geological analyses, biostratigraphic analyses. Basic geotechnical parameter values and assessment of geotechnical suitability of selected types of structures were also delivered.

United Kingdom

The Department for Business, Energy & Industrial Strategy (BEIS) is the competent authority for offshore wind energy in the UK (England, Wales, Scotland and Northern Ireland). In these countries, a lease from the Crown Estate is required. In this initial (pre-installation) stage, desktop studies based on available data from public and customer sources are carried out, generating a preliminary terrain model and assembling the project specification for preliminary surveys. The British Geological Survey (BGS) has mapped in detail the seabed around the UK and maintain a database with geological, geophysical and geotechnical information compiled from numerous oil and gas and consulting companies. The aim is to acquire a thorough understanding of the environmental and geological conditions and local sediment transport mechanisms for a variety of purposes, such as: Develop a baseline of the environmental conditions; Identify particular hazards along the cable route; Identify the installation methods that can be used; Predict long-term changes to the seabed, such as moving sand waves, that might need to be monitored. Information is required on the morphology of the seabed, presence of any debris, boulders and particularly UXO need to be identified. However, irrespective of the source of the information used in the desktop study, it is suggested that all data is validated (if inconclusive or of low quality) by experienced personnel before it is used in the study.

After the concession, the developer has a period of 36 months to conduct an initial feasibility survey when bathymetric, sonographic, seismic and magnetic surveys are conducted to update the seabed geological model, verify the existence of UXO, define geological and geotechnical sampling locations. There is no detailed specification for the survey, but "good practices", where the general demands of a survey for the different phases of the project, are provided. This survey will normally be dominated by geophysical methods to characterize the seabed, seabed mobility and shallow geology across the whole wind farm area. The methodologies include:

- Bathymetry (ideally over a number of years).
- Side-scan sonar survey.
- Echo sounder survey.
- Acoustic sub-bottom profile survey.
- Magnetometer survey.
- Drop-down video.
- Geotechnical probing (limited to drop cores or grab samples).

The feasibility survey will be able to provide sufficient information to gain consent for the geohazards associated to the generators and cable installation.

A further survey stage is required to provide installation contractors with the information they require to plan and cost the installation works. This survey includes environmental, geophysical and geotechnical testing and sampling, including (but not limited to):

- High-resolution bathymetry.
- Side-scan sonar.
- Sub-bottom profiling.
- Cone penetration testing.
- Vibrocore sampling.
- Grab sampling.
- Drop-down video.

The survey specifications (methods to be used, frequency of sampling and line spacing), are not clearly described, but are left to considerations on aspects related to the geology of the seabed and water depth. Special attention must be given to cable and pipeline crossings eventually requiring magnetometer and sub-bottom profiling if the cable or pipeline is buried.

After the construction phase, and to understand what was installed, post-installation surveys are carried out to verify that the transmission cables are buried to the required depth and correct position, avoiding cable damage from fishing, anchoring or other third-party activity. These are known as as-laid and as-built surveys. Four methods of inspection may be used to verify the cable condition: Acoustic inspection using towed or vessel-mounted sensors (typically side-scan sonar and multibeam echosounder); Inspection using 3D imaging sonar; Visual inspection using ROV's; and diver inspection (mainly limited by water depth).

United States

The Bureau of Ocean Energy Management of the United States Department of the Interior (BOEM) is the agency responsible to ensure the safe installation of future renewable energy facilities located on the Atlantic Outer Continental Shelf (OCS). This includes guarantee the studies are based on geophysical and geotechnical techniques and employing standardized methodologies. Site characterization should include the following activities: desktop studies, seabed geophysical and geotechnical exploration, and laboratory testing of collected sediment samples (BOEM 2020).

The final report must include information on seabed morphology and sediment variability, subseabed stratigraphy (including position of the rocky basement and presence of boulders), geological and anthropogenic hazards (including geological faults, shallow buried paleochannels, gas pockets and seeps, shipwrecks), slope stability, sediment mobility, strength, deformation and consolidation, and information of specific factors such as cyclic loading and sediment sensitivity. At the end, BOEM will review the results of survey for the information it provides on seafloor and sub-surface conditions as they pertain to the proposed projects' siting, design, construction, and operation. An interesting detail is that the survey area should cover not only the installation site, but the entire area potentially to be physically disturbed by the engineering activities.

In general, BOEM guidelines are as follows:

- The navigation system should be able to continuously determine the vessel's position, and the geodetic system should be consistent across all data types. The positioning's horizontal uncertainty should conform to the requirements of IHO special order surveys (± 2 m at a 95% confidence level). The use of USBL systems are recommended (not mandatory) to allow the positioning uncertainty of towed sensors such as side scan sonars to not exceed 10m. If USBL systems are not available, the use of calculated layback distances can be considered. Line spacing should not exceed 150 m throughout the project area with tie lines every 500 m maximum.
- Bathymetric survey should guarantee 100% seabed coverage. The vertical uncertainty of the measured depths should be consistent with the IHO Special Order survey from 0 to 40 m water depths, and with order 1A beyond that. The minimum resolution of the final bathymetric grid should be of 0.5 m in water depths shallower than 50 m and 1 m or better than 2% of water depth resolution beyond 50 m. Backscatter values from the seabed returns should also be logged and appropriately processed. Bathymetric light detection and ranging (LIDAR) methods are allowed in very shallow coastal areas where conventional bathymetric systems are ineffective.
- Regarding the sonographic survey, BOEM guidelines suggest the use of a towed, dual-frequency (200 to 600 kHz) side-scan sonar system to provide continuous mosaic of the seafloor allowing to characterize seabed habitats and sediment distribution, locate surficial boulders, and identify anthropogenic hazards and cultural resources. Swath range and line spacing should assure at least 100% overlapping providing resolution of objects 0.5m to 1.0 m in diameter at maximum range. The data should be post-processed to improve data quality so that the final mosaic shows a resolution of 0.5 m resolution or better.
- In the case of survey areas shallower than 100 m, a magnetic survey must be conducted to detect ferrous metals or other magnetically susceptible materials. The sensor, equipped with depth sensor or altimeter, should have a sensitivity of 1.0 nanotesla (nT) or less, and be towed no more than 6 m above the seafloor. The data sampling interval should not exceed one second. Background noise level should not exceed 3 nT peak-to-peak. The precise location of all buried pipelines and in-service cables within the limits of the survey area should be determined.

The specifications for seismic surveys are very qualitative.

- For sub-bottom profilers and Chirp systems the resolution should of 0.3 meters within the uppermost 10 to 15 m of sediment.
- Operational frequency should be between 0.5 kHz and 16 kHz, whichever allows the best resolution within the specified minimum investigation depth.
- For "medium penetration seismic systems", defined as a boomer, sparker, bubble pulser, or other low frequency system, the minimum penetration should be greater than 10m beyond any potential disturbance depth from a foundation (either a meteorological tower or wind turbine), anchor and /or spud penetration for a rig or work barge, or the burial depth of the cables, with a vertical resolution of at least 3 m.
- Sources should consist of a dual or triple plate (no frequency range is specified).
- To provide the highest resolution data, when using a 16- to 48-channel streamer, it must be positioned less than 1 m from the sea surface.

The data should be digitally recorded, to allow signal processing techniques to be employed in order to improve data quality. BOEM also recommends that the power level of the seismic sources to be 160-180 dB re 1 µPa (RMS), limit considered as Level B and Level A, respectively, harassment under the Marine Mammal Protection Act the National Marine Fisheries Service (NMFS).

A final report, with a comprehensive description of the survey results, should be delivered. This report must have, among other basic information, the technical specifications of survey equipment and procedures, a Cable Route Position List (in both tabular and GIS shapefile formats), and a set of charts (navigation, bathymetry, geologic surface and subsurface features, and magnetic contour) at a 1:10,000 scale.

DISCUSSION

When we speak about "marine geophysical methods" in the general sense, it is consensus that they are a very useful, fast and reliable tool to identify and assess the risk of surface and buried geohazards. Offshore geohazards consist of a variety of seafloor processes and features that may represent potential danger to offshore infrastructure and coastal communities causing loss of life or damage to health, environment or field installations (Micallef et al. 2018, Kvalstad 2007). Examples are submarine slides, channels, canyons, gullies, steep slopes, shallow gas and water flow, salt and mud diapirs, bottom currents, overpressure zone, geological active faults, reefs, rock outcrops, beach rocks, scouring, mounds and ridges. Additional risks may be posed by anthropogenic hazards, those predominantly produced by human activities, such as the construction and operation of offshore or subsea infrastructures, marine traffic, waste disposal and fishing, which eventually leave a series of debris dumped, swept, blown or intentionally discarded from vessels or platforms at sea. Therefore, when planning a geophysical survey to "to obtain adequate information to establish a geological understanding of the areas, providing input to environmental, archaeological and UXO evaluations and subsequent geotechnical campaign", the people involved must consider locating targets in different size and time scales. And that depends on the survey configurations.

As demonstrated, there are different regulations regarding what is necessary, in terms of geological, geophysical (and, consequently, environmental and archaeological) survey, to evaluate the engineering risks associated with the installation of an offshore wind farm. Some countries give very specific guidelines of which technique should be considered, while others give only general specifications. However, most of the instructions provided are essentially related to engineering issues.

Previous data and desktop studies

Some countries, such as Denmark, The Netherlands and the United Kingdom make previous geophysical and geotechnical data available to potential wind farm developers. With these data they can preliminarily plan where to locate the structures, define survey configurations and pre-locate geotechnical coring sites. The main aspect here is to provide the developers with information to help decision making and reducing risks and costs to the project. It is an interesting measure, but not feasible to countries with wide territorial waters. Countries with long offshore oil and gas exploration history, such as the United States, Brazil, United Kingdom, may have plenty of data available, but these are spread among different companies, which seldom open this kind of information. Also, nowadays, most of the exploration takes place in very deep waters and, despite some projects to develop wind farms farther offshore, almost all the projects are focusing on the inner continental shelf.

Repeated surveys for different stages of the project

The project of an offshore wind farm consists basically of five stages (Development; Constructions; Execution; Operation and Monitoring; and Decommissioning). From the analyzed countries, France, Germany and the UK demands different surveys for different stages of the project. The complexity of the surveys increases as the project develops. It is obvious that an IHO Special Order survey will demand better (and more expensive) equipment, more survey lines and longer data processing time than an IHO order 1B survey. But the question here is: Are multiple, shorter and with increasing resolution surveys (such as France which demands refractions seismic and MASW to determine Vp and Vs) a better option than a single, longer and more detailed survey, able to gather all information needed for all stages of the project at once? The answer will depend on several factors, such as the weather window, mobilization costs, geological complexity of the area, ship availability and the amount of resources available at the initial stage of the project.

Positioning

Offshore site surveys require the positioning of a survey platform (survey vessel, underwater vehicle or towed body) with high relative accuracy. At present the Global Navigation Satellite Systems (GNSS) include the American GPS, the Russian GLONASS and the European GALILEO systems. Therefore, the number of satellites is not the problem. The most important factors to guarantee a good positioning of the survey vessel are the number of satellites and their geometrical configuration in the sky. Additionally, all offsets between the positioning antenna and all survey sensors must be precisely determined. Most countries have defined the minimum positioning accuracy, but the range of values is very large, from 0.5 m (Denmark) and 5 m (Germany) for hull-mounted systems, and 2.5 m (Denmark) and less than 10 m (Germany and United States) for towed systems. Denmark specifications are even stricter than IHO Exclusive order. Submarine acoustic positioning systems may be used to position towed systems such as side scan sonars and magnetometers. The position is calculated based on range and direction measurements, giving the relative position between the tow-fish and the system's transponder. However, these systems are not so effective in shallow water areas, as the survey vessel is in a position too oblique relative to the sensor. Moreover, shallow water environments are very noisy, affecting the signal-to-noise ratio of the received signal, reducing the system's ability to make precise positioning measurements. The use of cable layback must be carefully applied, since it needs a rigid control of the amount of cable in the water and the angle relative to the vessel's longitudinal reference axis.

Bathymetry

All countries demand a full coverage survey with 50-100% overlapping. This configuration provides a digital bathymetric model (DBM) with a resolution better than 0.5 m. But regarding the Total Vertical Uncertainty (TVU) of the bathymetric measurements, most of the countries use the IHO S-44 Standard for Hydrographic Surveys. While the United States demands Special order TVU (≤ 0.25 m), Germany and Denmark specify 1A and 1B orders (0.5 m). Other countries such as France, Holland and the United Kingdom gives no details about the TVU. The higher the resolution of the DBM and the lower the TVU, the better the definition of the seafloor's morphology. This is a critical issue for the identification of geohazards like coral reefs and Rhodolith beds (which are a major environmental concern), sand waves (which indicate mobile sediments), beach-rocks, small bathymetric depression such as pockmarks, bedrock outcrops, shipwrecks and more. Most of the countries considered in this research give no details about the use of backscatter data. Only France and the United States "recommend" the use of backscatter data but give no detailed specification. It is important to highlight that this tool is able to map the sediment distribution of the seafloor and has been used in several projects regarding the study of geohabitats, a very useful tool for environmental evaluation.

Sonography

All analyzed countries demand full coverage, dual frequency sonographic surveys. Overlapping ranges from 50% (France) to 200% (Denmark). Germany, Holland and the United States are more specific about the frequency to be used (≥ 100 kHz, 100-600 kHz and 200-600 kHz, respectively), as well as about the minimum detectable size of objects on the seafloor, which ranges from 0.2 m (The Netherlands) to bigger than 1m. There are some aspects to consider here: first, ideally, the dual frequency survey should be conducted simultaneously, that is, the equipment used should be able to acquire data at both frequencies at the same time (and not all equipment does that!). This would have a huge impact on reducing survey costs, since the option would be to conduct two surveys, doubling the time needed to complete the survey. The second point is that the higher the frequency used the smaller the swath. Standard 100 kHz equipment can survey a corridor up to 1200 m wide (600 m for each side), while 500 kHz equipment would be limited to survey a corridor not wider than 150m (75 m to each side). Therefore, in order to fully cover the area with both frequencies, line spacing would be defined by higher frequency swath. Obviously, the smaller the survey corridor the higher the resolution of the survey, and greater the ability to locate debris on the seafloor. The third aspect to consider is the overlapping. Standard overlapping for sonographic surveys is 30%. This is enough to guarantee that no voids would be left in the survey (considering that the navigation is straight). Overlapping of 100% means that the area is covered twice. In this case lines next to each other should be run in opposite navigation courses, ensuring that every part of the seafloor is ensonified, leaving no acoustic shadows on the seafloor, increasing the definition of the identified targets. In summary, if the spacing of survey line is controlled by the swath width of the high frequency survey, and if the survey must fully cover the area with 100% overlapping, a simultaneous lower frequency survey would not be effective, as the low frequency mosaic would have a much lower resolution, with impacts on data storage and processing costs. On the other hand, multispectral (or multifrequency) surveys are proving to be a leading edge on geophysical surveys. As the acoustic response of the seafloor is frequency dependent, side scan sonars able to operate in two frequencies simultaneously, can provide different information about the seafloor.

Seismic

The specifications for seismic surveys for offshore wind farms vary greatly. Sub-bottom profilers and Bommer/Sparker systems are mandatory in all cases. These are the usual seismic systems used in all site surveys for subsea engineering projects. For sub-bottom profilers the investigation depth varies from a minimum of 7.5 m (The Netherlands) to 15 m (United States); the vertical resolution ranges from 0.1 m (The Netherlands) to 1 m (France). For boomer and Sparkers systems, the investigation depth ranges between 50 and 100 m. In the United States the guidelines demand “10 m below disturbance depth”, which is approximately 100 m below the seafloor. Vertical resolution should be as low as 0.5 m (The Netherlands) up to 3 m (United Sates). Inline spacing varies from 100 m (Denmark) up to 500 m (Germany), while crossline spacing varies from 750 m (The Netherlands) to 1000 m (France). The main objective of seismic surveys is to identify buried geohazards, like paleo-channels, biogenic gas pockets and geological faults. These are features that may have hundreds of meters in size. Line spacing is critical here, as it must be compatible with the size of the geological hazard to be identified. The line spacing defined by the guidelines is compatible for this task. With crosslines it is possible to build a pseudo-3D volume. However, for more detailed information required for specific tasks, such as locating small scale geological hazards (buried coral reefs, boulders, etc.) definition of geotechnical coring sites and positioning of turbine foundations the specified survey line spacing may not be acceptable. Is this case, an Ultra-High-Resolution Survey (UHRS) is needed, and Denmark is the only country which specifically demands this system. Marine ultra-high-resolution seismic (UHRS) tend to be characterized by signal frequency ranges of 0–600 Hz, bin sizes of the order of 3 to 6 m and vertical resolution smaller than 0.5 m (Monrigal et al. 2017). To achieve this level of resolution, line spacing should be reduced to 10-20 meters apart, with huge impacts on the survey time and budget. Recently, a new 3D multichannel Ultra High Resolution Seismics (3DmUHRS) system has been commercially available (Mikalski 2023). It uses a multi-tip sparker source delivering high-energy output and a broadband high-frequency spectrum (up to 2.5 kHz.) in substitution for the small airguns. These systems can provide a seismic volume with 1.0 m bin size and 0.5 m vertical resolution. France also demands refraction seismic and Multichannel Analysis of Seismic Waves (MASW) for the P- and S-waves speed determination, respectively. Seismic velocities, which depend on the elasticity and density of the subsurface material, are used to estimate rock strength and rippability (Azadi et al. 2020). This method uses refraction first arrivals to compute speed and thicknesses of shallow sedimentary rock layers (Mitchell & Bolander 1986).

Magnetometer

Magnetic surveys are used to locate metallic debris on seafloor, such as shipwrecks and UXO's. These are essentially small objects, ranging from 1 to 100 m. Due to this target size, survey lines must be very close to one another. Specifications demand the use of gradiometer, which is a type of magnetometer consisted of two or more sensors, that measures the rate of change of the magnetic field (gradient and spatial variation), increasing the accuracy and the sensitivity of the measurements. To increase the performance of the equipment and achieve

Table I. Resume of the main aspects to be considered for a geophysical site survey.

Desktop studies	All previous data available should be used on a desktop study of the area. Any knowledge about the seabed geological/oceanographic/environmental conditions is of great importance for planning survey operations and engineering activities.
Positioning	GNSS system is today the most straightforward way vessel positioning. To achieve resolution better than 1 m, the differential correction is mandatory. It is important to have a real time quality control of the vessels position by observing variables such as the number of satellites in view, the position dilution of precision (PDOP) and the time lapse of the differential correction messages. These variables are all made available by commercial GNSS systems.
Bathymetry	A full coverage bathymetric survey with IHO Special Order resolution would allow to map small variations on the seabed morphology with enough resolution, as well as serve as a good basis for geohabitat and environmental studies. Multibeam systems are the most practical equipment for the task. As the swath area is proportional to the water depth, a large amount of survey lines may be necessary to cover the whole area.
Backscatter	The inversion of the backscatter data to sediment type, complemented by ground truthing (geological samples, bottom imaging), is also important for superficial geological mapping and geohabitat investigation.
Side Scan Sonar	A full coverage side scan sonar survey with 100% overlapping to guarantee that every portion of the seafloor has been scanned, must be conducted. It facilitates the identification of any debris on the seafloor. The higher the frequency the better the mosaic's resolution, but the narrower the swath width. Frequency and swath must be compatible with the multibeam, to optimize the amount of survey lines.
Multispectral seismic	The integrated interpretation of sub-bottom profiler and Sparker/Boomer data, with frequencies ranging from 200 Hz and 10 kHz, provides very high resolution in the upper 2-3m of the seafloor (for cable burying) and investigation depth below the seafloor up to 100 m (for foundation studies). Post-processing should be considered to improved data quality and reliability of the information. Applicants should be aware that acquisition and processing of shallow water multi-channel seismic data is highly technical and complex. However, despite the elevated costs associated to a 3D seismic survey, it may be a good option in geologically complex areas.
Magnetometer	This survey is critical in areas where UXO's represent a real threat to the operations. In this case line spacing between the survey lines should be as small as possible and the equipment should be towed as close as possible to the seafloor to enhance data resolution. For the detection of shipwrecks line spacing can be bigger, as the anomalies resulted from these targets are very large and easily detected.

the specified resolutions of less than 1 nT, it should be towed at a distance at least 3 times the vessel's length, and as close as possible to the seafloor (less than 6 m). UXO's are a real problem in Europe and, in some measure, on the east coast of the USA. In other countries the main magnetic anomalies are related to shipwrecks, which are much bigger and can be easily detected with a magnetometer.

In general, offshore wind farm developers routinely rely on third party geophysical survey companies for data acquisition. In spite of the fact that these companies have been carrying out geophysical surveys for subsea engineering projects for a long time, a communication and knowledge gap seems to persist between the parties involved (Dyer 2011). It must be said that all parties have a common interest in acquiring accurate and relevant data, because reliable information is the basis to support decision making. The contractors, the ultimate end user, often have little or no input in the manner in which the geophysical (and geotechnical and environmental) data should be acquired, processed and reported. This is usually defined by governmental regulatory agencies or by the survey companies itself, as they are considered the "specialists". For offshore wind farms is also common to "copy and paste" guidelines from the oil and gas industry. This can end in a situation where non habilitated people write survey specifications for equipment and methods of which they have insufficient understanding, for geophysicists, who, in turn, understand the equipment and methods but do not have the skills in subsea engineering to report the data in a way that focuses on issues relevant to the project developers (Dyer 2011). Trying to avoid this communication gap, the German regulatory agency highlights that the final report shall be set up "from an engineering geological point of view", whatever this means.

For countries with extensive maritime zones, such as Brazil, one single survey specification may not work. Figure 7 shows the location of the offshore wind farms submitted to the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA). The diversity of geological and oceanographic conditions along its 7,367 km long coast (Vitte 2003), results in a variety of regional specific geohazards which, in turn, demand different survey specifications. A survey at the northeastern coast cannot have the same specifications for a survey in south Brazil. The geology of the seafloor, and consequently the geohazards, are not the same. Likewise, one single specification encompassing all possible geohazards would be inefficient, as survey costs would be prohibitive.

New technologies

The development of marine geophysical tools has increased tremendously in recent times, leading to improved resolution, accuracy, and efficiency in data collection and interpretation. Moreover, advances in computer processing capability, transducer technology and data integration has resulted in a better understanding of surface and subsurface structures and geology, These are all important elements in reducing the project risk and improving its economic viability.

Interferometric sonars, also known as Phase-Measuring Bathymetric Sidescan (PMBS), have been presented as an alternative technology for the standard Multibeam Echosounder (MBES) systems for bathymetric mapping. It is essentially a side scan sonar and consists of a series of vertically arranged transducers (one transmitter) spaced at a distance multiple of the signal's wavelength. Pimentel et al. (2020) states that, compared to conventional MBES, this system has greater swath capability in shallow waters (up to 10 times the water depth), providing better visualization at the edges of the swath,

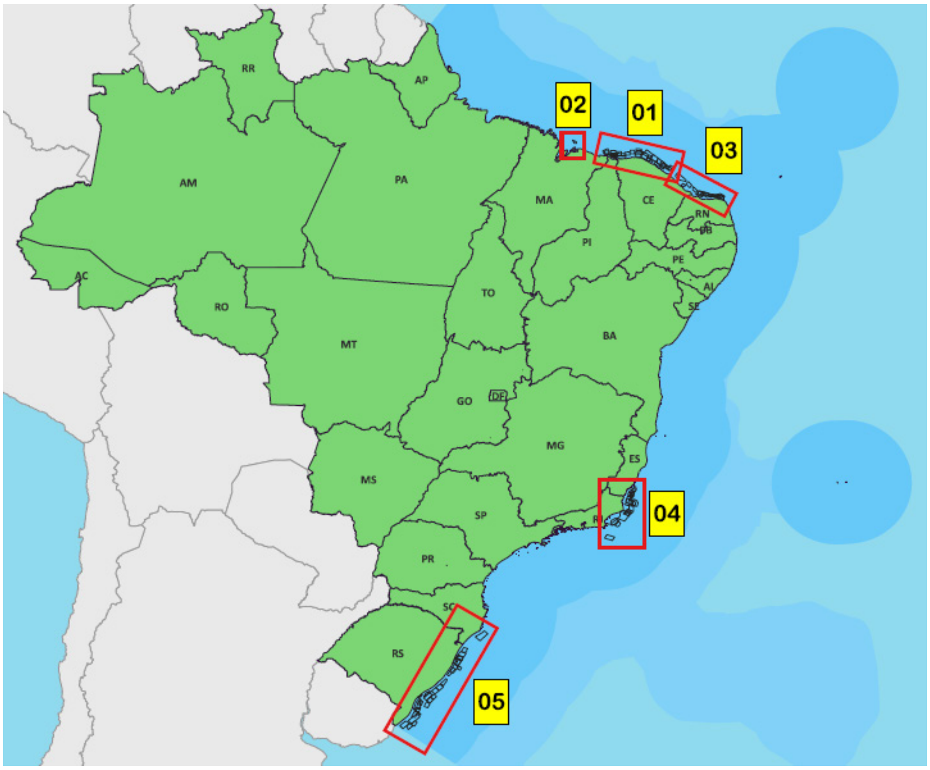

Figure 7. Location of offshore wind farm projects with environmental processes open at the environmental agency IBAMA. Source: https://www.gov.br/ibama/pt-br/assuntos/laf/consultas/arquivos/20240507_Usinas_Eolicas_Offshore.pdf.

has much higher data density, which may lead to across-track resolution down to 30 mm. But the system has also some disadvantages (R2Sonics 2024). At nadir, where all returns have an incident angle close to 90º and there is negligible time difference between the returns, the system creates a blind spot immediately below the sensor. This, added to the non-ensonified areas, demands an overlap of 100% of the survey lines to ensure full coverage of the area surveyed. Moreover, interferometric systems are unable to distinguish between acoustic returns arriving from different angles at the same range, which makes them unable to distinguish returns from very steep targets. They are also very sensitive to the platform's remote positioning and attitude (heave, pitch and roll). Pimentel et al. (2020) showed that interferometric sonars were able to achieve Special Order TVU. However, its data showed high dispersion, which made the node sample uncertainty to agree only with IHO Order 1A specifications.

Another technology that has matured substantially in the last few years is the Synthetic Aperture Sonar (SAS). It is a recently new underwater imaging technique with extraordinary area coverage, providing imagery with high degree of spatial resolution (< 10 cm) by coherently co-registering the returns from multiple pings with slightly different geometry of the same scene to synthesize a large acoustic aperture (Sternlicht & Pesaturo 2004). The main advantage over conventional side scan sonar is that SAS offers the potential for high-resolution, range independent, along track resolution. It has been used on some mine hunter activities for some year, but recently SAS has been recognized as a valuable tool for submarine pipeline inspection, oil fields decommissioning projects and underwater archeology (Fernandes et al. 2021, Ayres Neto et al. 2017, Ødegård et al. 2018). The improved resolution comes, however, at the cost of increased data volume and computation time, as for good post-processing of the data and image formation, the position and motion of the towfish need to be exactly known. It is, therefore, not recommended to be used as a towed system. On the other hand, by being essentially a side scan sonar regarding the operation, it must be towed at a certain altitude over the seabed (between 10-20% of the swath width). This condition, together with the need to acquire high-resolution sonographic images, limits the use of hull mounted SAS systems in areas deeper than 30 m. Ideally, this system should be used in AUV.

There are systems on the market that combines both interferometric bathymetry and synthetic aperture sonar. This system is capable of simultaneously acquiring detailed bathymetry combined with very high-resolution images of the seabed, providing incredible digital terrain models of the seafloor.

A lot of effort has been put into the further development and implementation of unmanned maritime vehicles (USV and AUV) in the last decade. The main drivers behind this development are to reduce human exposure to hazardous environments and to enable more sustainable operations by consuming less fuel than traditional survey vessels, reducing greenhouse gas emissions. There are, however, some issues that should be considered. AUV operation in shallow water is not trivial, as real time positioning from a support vessel by means of an USBL system is not very efficient due to environmental noise which hinders signal-to-noise ratio reducing the accuracy. Also, the control of AUV's in shallow water is made more difficult by the effects of ocean waves. Wave effects can drastically change the heading, speed, and location of the AUV (Sabra 2003).

However, the combination of these new technologies still needs some time to prove their causes, as it involves rethinking the whole concept of hydrographic 'operation'. Greater progress will indeed be made once developers and service providers adapt their survey methodology to the use of these new remotely supervised platforms.

CONCLUSIONS

According to the International Energy Agency and the International Renewable Energy Agency, the world needs to deploy 2,000 GW of offshore wind energy by 2050 to meet net-zero scenarios that avert catastrophic climate change. There are 115 sovereign nations with enough offshore wind to generate power, but, so far, only 19 countries have operational offshore wind power. Offshore renewables can and should be expanded and sited in a way that is environmentally responsible. The main objective of a geophysical survey is to understand the geological and geotechnical characteristics of the seafloor and recognize the submarine geohazards associated with it.

However, the optimum geophysical survey design is a compromise between the necessary information level and quality demanded by the objectives of the project and cost effectiveness. Consideration must be made about which techniques should be used and with which configurations they must be operated in order to achieve the desired vertical and horizontal resolution/accuracy. It is consensus that all geophysical tools must be used, as each one delivers specific information about the seafloor. Also, the same system can be operated at different frequencies, allowing different approaches to the same question. The integrated interpretation of all data is key to resolving ambiguities in the geophysical data. The quality of the data must always be considered. Bad quality data results in more processing time, and most of the time, in inaccurate interpretation leading to under- or over-optimistic assessments of geohazard risk, with serious impact on the project.

As demonstrated, there is no standard survey configuration. It changes from country to country. However, they mostly agree on which techniques are to be used: multibeam echosounder, dua-frequency side scan sonar and high-resolution seismic. And it should be so! A standard survey procedure may be useful in countries with small contiguous oceanic areas. For countries such as France and USA, which due to its overseas departments and territories scattered all over the world, giving them the two largest exclusive economic zone in the world, or Brazil with its EEZ 7.5 million km², it is impossible to have a general site survey guideline. The plurality of geological environments which, in turn, implies a multitude of possible geohazards, demanding very specific survey designs according to the region.

In the Brazil case, it is essential to deliver a general assessment of all possible geoharzards to be found along its territorial waters. Offshore wind farm projects are being planned mostly in the northeast, southeast and south regions of the country. Each of these areas have unique geological, geotechnical and environmental characteristics that, to be precisely recognized, demand specific survey specifications and procedures. Brazilian regulatory agencies must comprehend that a generic survey solution must not be effective in recognizing risks that are particularly related to a specific geological environment.

It is, therefore, crucial to conduct systematic investigations to assess the implementation risks and to monitor the long-term environmental effects of offshore wind farms on marine ecosystems. Desktop studies are important to provide information to prepare the best survey design and specifications. By integrating comprehensive physical and biological observations with advanced modelling approaches, geoscientists can enhance our understanding of the effects of producing renewable energy in the marine environment. This knowledge can be attained by means of geophysical surveys designed to identify the hazards related to each geological environment. This is vital for developing sustainable offshore energy policies that minimize environmental impact while maximizing the benefits of clean energy generation.

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Data will be made available upon reasonable request.

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