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Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil

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ABSTRACT

The objective of the paper is to perform a review of the environmental impacts of the installation, operation and maintenance (O&M), and decommissioning of offshore wind technologies. At first, a comprehensive review is presented on offshore wind technologies and techniques related to the installation, O&M, and decommissioning stages. Then a thorough review of environmental issues using the main available studies in the literature associated with the activities of each stage is performed. The review employs an activity–stressor–receptor–impact framework in which the possible positive or negative impacts of an environmental stressor on a specific receptor are identified for each activity, such as pile driving, cabling, blade rotation, etc. Additionally, a case study of Brazil addresses regions with biological resources, marine protected areas, and offshore wind hotspots considering atmospheric reanalysis along the coastline. Moreover, the presence of the offshore oil and gas (O&G) industry is discussed as an important influence on the development of offshore wind projects in Brazil.

1. Introduction

The worldwide offshore wind industry has shown excellent potential for generating electricity, with an average growth of nearly 30% per year since 2010 [1]. In 2019, the offshore wind industry added 6.1 GW to the 23 GW total installed capacity by 2018, reaching more than 29 GW for the total installed capacity. It represents 4.5% of the total cumulative capacity (651 GW) from wind power total installed capacity [2]. Although wind energy generates about 5% (1.27 TWh) of the global electricity supply and represents a 2% share of the global energy matrix [3,4], cleaner electricity generation needs the further participation of renewables in the global energy matrix to accelerate energy transition [1]. Offshore wind is one of the most promising resources, with a target generation of about 600 TWh, determined by the International Energy Agency (IEA), according to the sustainable development scenario for 2000–2030 [1]. Over the next five years, about 150 new offshore wind projects are scheduled to be completed around the world [1]. In 2019, offshore wind bids reached the lowest winning values of £ 39.7/MWh in the UK, € 44/MWh in France, and € 49.9/MWh in Denmark [2]. These values are still higher when compared to other energy resources, such as onshore wind and solar PV [5]. In Brazil, in 2019, the onshore wind bid was raised to BRL 67.7/MWh, and the solar PV bid raised to BRL 118.4/MWh in 2017 [2]. The costs of developing the offshore wind energy (OWE) industry have decreased in the last years, and specialists have foreseen these costs as competitive in the next decades [1].

Abbreviations: AL, Alagoas; ANEEL, National Electric Energy Agency; ANP, National Petroleum Agency; AP, Amapá; BA, Bahía; CE, Ceará; CLV, Cable-laying vessel; CTV, Crew transfer vessel; EEZ, Exclusive economic zone; EIA, Environmental Impact Assessment; EIS, Environmental Impact statement; EPE, Energy Research Office; ES, Espírito Santo; GHG, Greenhouse gas; GWEC, Global Wind Energy Council; HDD, Horizontal directional drilling; IBAMA, Brazilian Institute of Environment and Renewable Natural Resources; IEA, International Energy Agency; IPU, Integral protection units; JUB, Jack-up barges; KPI, Key performance indicator; LCOE, Levelized Cost of Electricity; MA, Maranhão; MMA, Ministry of Environment; MME, Brazilian Ministry of Mines and Energy; MSP, Marine spatial planning; MW, MegaWatt; O&G, Oil and gas; OWA, Offshore Wind Area; OWE, Offshore Wind Energy; OWF, Offshore Wind Farms; PA, Pará; PB, Paraíba; PE, Pernambuco; PI, Piauí; PV, Photovoltaic; RJ, Rio de Janeiro; RN, Rio Grande do Norte; ROV, remotely operated vehicles; RS, Rio Grande do Sul; SC, Santa Catarina; SCADA, Supervisory control and data acquisition system; SE, Sergipe; SEA, Strategic Environmental Assessment; SP, São Paulo; SUU, Sustainable use units; TLP, tension-leg platform; UK, The United Kingdom; WTIV, Wind turbine installation vessel

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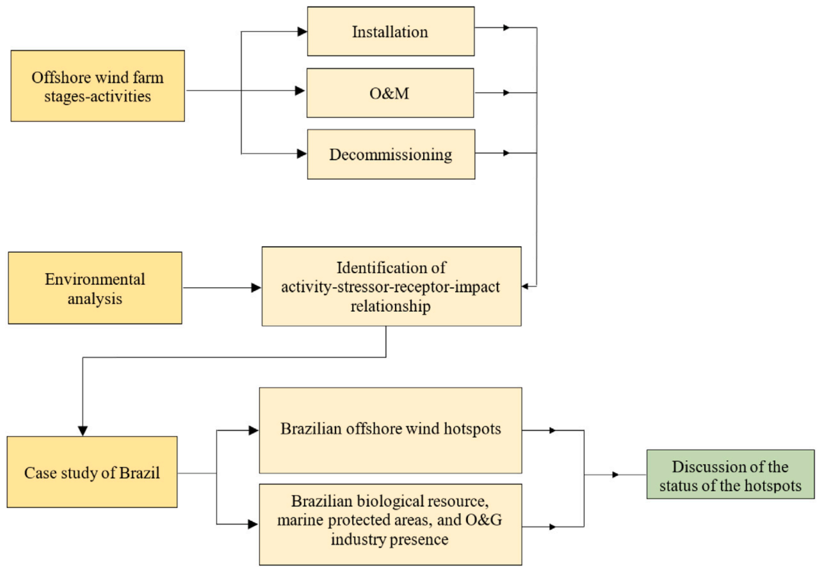

Fig. 1. Flowchart of the paper approach.

The global market is evolving rapidly, and new interesting markets are emerging. Currently, Europe and China are the most important markets for offshore wind. The United States, Korea, India, and Japan have manifested ambitious goals with significant expansion towards about one-quarter of the global installed capacity by 2040. Other countries with vast offshore wind resources such as Brazil, South Africa, Sri Lanka, and Vietnam have shown interest in the World Bank's offshore wind emerging markets [1].

A key consideration is that every energy project may cause impacts on the natural, social, and economic dimensions [6–8]. The Crown State (UK) [9] outlines that based on European legislation, the developers must carry out an environmental impact assessment study that specifies the impacts on human health, climate change, and biodiversity to guarantee the sustainability of energy projects, especially for projects in larger scales, as the case of OWE.

Since 2018, policymakers have debated the promotion of electricity generation using wind and solar resources in the Brazilian inland waters and exclusive economic zone (EEZ), including territorial waters [10]. A Bill to regulate the authorization for the generation from offshore renewable sources, including offshore wind, is under analysis in the Brazilian Parlament since the beginning of 2021 [11].

In 2019, the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and the European Union sponsored the project "Environmental Impact Assessment of Offshore Wind Complex". This project analyzed the environmental assessment processes and environmental permission of offshore wind farms (OWFs) in six European countries, including Germany, Denmark, Belgium, France, Spain, and Portugal. The main findings suggested the necessity of developing strategic environmental assessment (SEA) studies that seek to prevent and minimize the adverse effects as well as to maximize the positive impacts of OWFs [12,13]. This study also highlighted the importance of strengthening knowledge about changes that those activities may produce on the environment [5,14]. The IBAMA is analyzing the licensing of five large-scale OWFs, with more than 300 MW of installed capacity: three located in the northeast, one in the south, and the last in the southeast of the Brazilian coastline [5]. Recently, the IBAMA released a Term of Reference to guide the environmental licensing for this project typology [15].

In 2020, the Energy Research Office (EPE) published the Road map for offshore wind in Brazil [5] showing a vast potential of offshore wind, approximately 700 GW in areas up to 50 m in depth. However, until now, no specific goals have been established by the government for developing this renewable resource. Additionally, the report showed the need to improve the Brazilian regulatory framework to meet the OWE industry's necessities.

This paper presents an environmental review approach in which environmental impacts are associated with specific offshore wind project activities during installation, operation and maintenance (O&M), and decommissioning. Afterward, the case study of Brazil presents offshore wind hotspot regions, using an atmospheric reanalysis model, biological resources, and marine protected areas along the coastline. Additionally, possible conflicts and synergies are discussed in the context of the offshore wind industry with the offshore oil and gas (O&G) industry along the Brazilian coastline.

2. Study approach

The different technical characteristics of an OWF such as foundation, turbine size, array layout, installation methods, O&M, and decommissioning techniques, may generate specific local impacts on the local ecosystems, communities, or economic structure [6]. Likewise, scaling the productive chain through increasing the turbine size or projecting larger OWFs might increase the significance of these local impacts and generate cumulative and synergic impacts [6,7,12,16]. Thus, the OWE development in large-scale and the inclusion of other activities such as offshore O&G and marine transport should be considered within SEA or marine spatial planning (MSP) efforts [8].

Understanding the relationship between the activities associated with an OWF and their specific impacts is essential. Taormina et al. [17] mentioned that when talking about anthropogenic disturbances, it is important to distinguish 'effects' from 'impacts'. Boehlert and Gill [18] explained those two terms and developed a conceptual framework for understanding their relationships. The "effects", also called "stressors", are modifications of environmental parameters, such as the substrate type, hydrodynamics, water temperature, noise, or electromagnetic fields beyond the range of natural variability. Consequently, the "impacts" correspond to the changes observed at the "receptor" level, e.g., the ecosystemic compartments (biotopes, biocenosis), ecological levels (populations or community), some ecological processes within marine ecosystems (trophic interactions), and others. Therefore, this work presents an approach in which the activity–stressor–receptor–impact relationship is identified during the installation, O&M, and decommissioning activities.

Fig. 1 depicts the step by step flowchart of the paper's approach. At first, we present a review of the state of the art of the OWF activities, including installation, O&M, and decommissioning. In sequence,

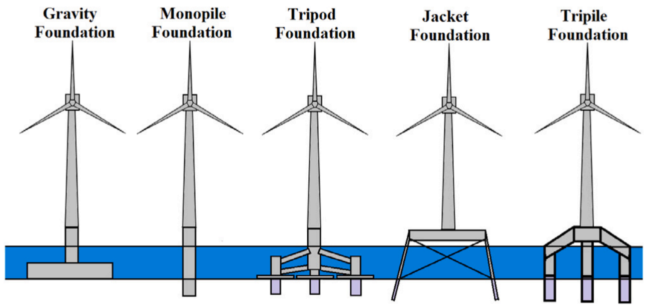

Fig. 2. Bottom-mounted foundations of offshore wind turbines.

a comprehensive review of the environmental impacts associated with OWFs is presented, in which the focus is on the identification of the stressors, receptors, and impacts associated with each specific activity. The last part addresses the case study of Brazil, where a comprehensive review presents the biological resources, marine protected areas, and presence of the O&G industry, which represents the largest share of the Brazilian internal energy supply [19], along the coastline. Additionally, an atmospheric reanalysis is used to identify the main energetic regions, in this study denominated as "hotspots", of the Brazilian coastline. Then we discuss the status of these Brazilian hotspots, addressing the environmental issues associated with offshore wind harnessing, considering the specific environmental characteristics of the Brazilian coastline, as well as its coexistence with the O&G industry.

3. Offshore wind technology

3.1. Foundation types

There are two main types of foundations for the offshore wind turbine industry: floating and bottom-mounted foundations. The bottom-mounted foundation concepts are suitable for specific water depths, usually up to 60 m. However, for water depths deeper than 40 m, these structures experience large hydrodynamic loads, which leads to an increase in the cost caused by an increase in their dimensions [20]. To overcome this issue, floating concepts have been proposed. As Fig. 2 shows, the bottom-mounted foundation type can be categorized into five types: gravity, monopile, tripod, jacket, and tripile foundation.

Additionally, the floating foundation type can be categorized into three general types, namely, semi-submersible, spar, and tension-leg platform (TLP) foundation, as shown in Fig. 3.

Fig. 4 shows the distribution of the foundation types that have been installed up to 2019 [21]. As shown, the monopile type has the largest share of the installation, following by the jacket type. Only a few

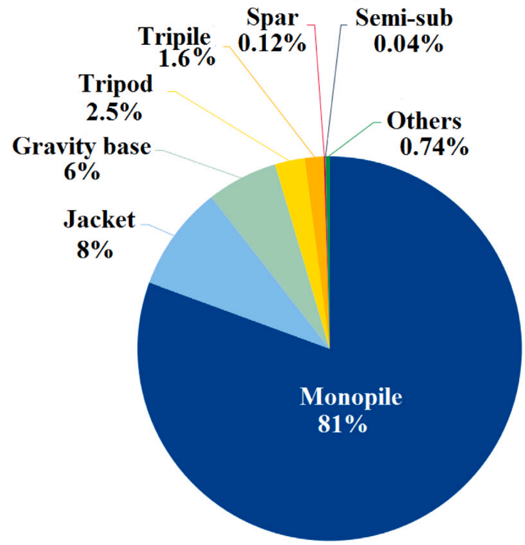

Fig. 4. Percentage of usage of each foundation type [21].

projects deployed the floating foundations. So far, the only commercial floating wind farm is the Hywind Scotland, installed in late 2017, which includes five floating wind turbines, with a spar type foundation, of 6 MW each. Some examples of the semi-submersible type are the Windfloat, Sea Angle, Eolink Prototype, and Kincardine projects, which are in the pre-commercial stage [21].

Although the evolution of the floating wind turbines is promising, the focus of this work is on the bottom-mounted type of foundation. The following sections describe the detailed process of the installation, O&M, and decommissioning stages.

3.2. Installation stage

The complexity of offshore wind farm installations is an essential factor, which considerably affects the offshore wind farm's cost. In this regard, as mentioned in [22,23], the weather condition and sea state, unforeseen ground conditions, damage to construction vessels caused by storms encountering unexploded explosives, and inexperienced installation teams cause delays in the installation process. Accordingly, several works have focused on the simulation and optimization of the installation process of OWFs, as reducing the installation time is the key to reduce the cost of offshore wind turbine installations.

As shown in [22], offshore wind turbine installation time has decreased over the recent years due mainly to the enhancement in the

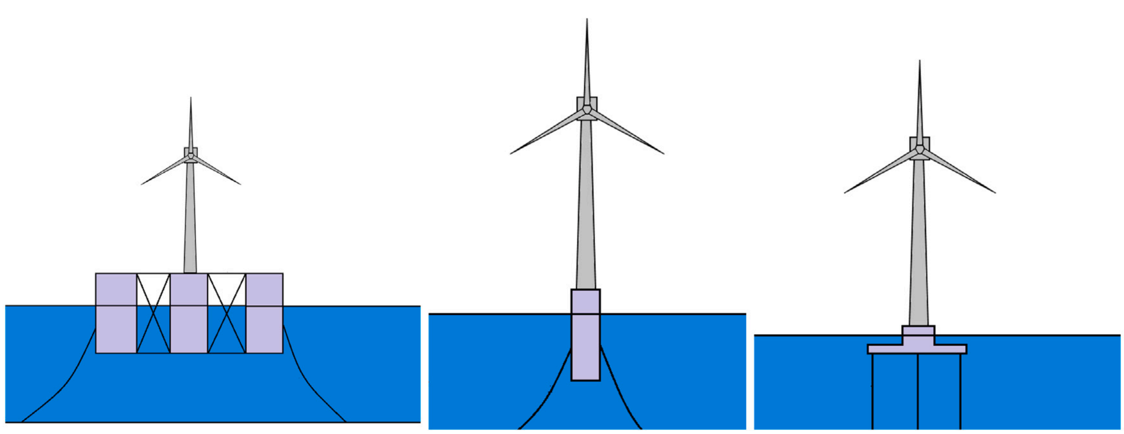

Fig. 3. Floating foundations of offshore wind turbines. From left to right, semisubmersible, spar and TLP type.

Fig. 5. Vessels used for the installation of offshore wind farms. Purpose built installation vessel (left), Jack-up barge (right), [24].

installation of the foundations. Irawan et al. [25] developed a mathematical model for the installation schedule to optimize installing an offshore wind farm in total installation cost and time. Thies et al. [23] evaluated the performance of installation vessels used in UK offshore Wind Rounds 1 and 2 by modeling offshore wind farms' installation using a probabilistic simulation tool. The results showed the dominant effect of the weather condition on the performance of vessels. Scholz-Reiter et al. [26] proposed an optimal installation schedule for offshore wind turbines to minimize the effect of bad weather conditions. Sarker and Faiz [27] optimized the turbine installation process by minimizing the total installation time by developing a mathematical model. Additionally, Leontaris et al. [28] proposed a mathematical model that considers the dependence of installation activities on each other in offshore wind farms. The authors claimed that this approach reduces the uncertainties associated with the installation time and cost. Besides, Vis and Ursavas [29] created a decision-support tool based on a simulation where different logistical concepts of offshore wind turbine installation are implemented to provide the optimal logistics approach.

However, as mentioned in [22], over the last two decades, the installation process has undergone few modifications, and what has decreased the energy cost is the increase in turbine size [22].

The main installation cost comes from the vessels used in the installation process [22,25,30]. As shown in Fig. 5, these vessels are subdivided into two principal types: purpose-built installation vessels and jack-up barges (JUBs).

Purpose-built installation vessels are specifically designed to respond to the offshore wind turbine demand. They are self-propelled and equipped with jack-up legs and cranes with high lifting abilities [23,31]. These vessels are also called wind turbine installation vessels (WTIV) [31]. These vessels' cargo capacity varies from 1300 tons to 8000 tons, and the area available on the deck for placing the cargo varies from 900 m^2 to 3750 m^2 [32,33]. The maximum operational water depths are between 24 m and 45 m, while the leg lengths vary from 32 m to 85 m [34]. The vessel speed ranges from 9 to 12 knots [35]. The JUBs, on the other hand, are also able to elevate themselves above the water surface using the jack-up legs [23,31]. As they are not self-propelled, they must be towed to the installation site at a speed of nearly 4 to 6 knots [32,35]. These vessels are also equipped with dynamic positioning systems, which enable them to remain at a fixed point to put their legs on a location with high precision. Compared to WTIVs, JUBs have lower cargo capacity, so the number of turbines they can carry is also smaller. JUBs can carry the cargo of weights between 900 and 2000 tons. Their available deck space varies from 400 m^2 to 2500 m^2 [32,33]. They operate in water depths ranging from 18 to 50 m, and the leg lengths change from 40 to 82 m [34]. Generally, offshore wind turbines' installation method varies based on the foundation and wind turbine type [36]. The foundation type selection depends on the water depth, wave/wind condition, seabed characteristics, and access condition [20,36,37].

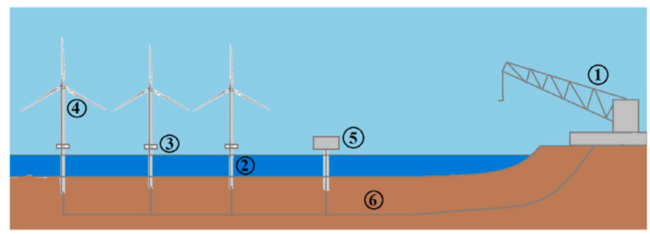

Fig. 6. Main steps in the installation of an offshore wind turbine.

The seabed conditions affect several parameters in the installation process of offshore wind turbines, such as the foundation type and the depth of penetration of the Jack-up legs [31,37,38]. It is also vital for the jack-up vessels to provide an adequate range of penetration in the seabed, which varies from 2 to 6 m.

The installation of fixed-bottom offshore wind turbines, as illustrated in Fig. 6, can be performed in six main steps [35]: (1) port logistics, (2) foundation installation, (3) transition piece installation, (4) turbine installation, (5) substation installation, and (6) cable-laying operations.

3.2.1. Port logistics

Port logistics constitute an essential part of wind turbine installations, as they provide bases for WTIVs and necessary equipment for loading and pre-assembling wind turbine components, i.e., the blades, hub, nacelle, tower, transition piece, and foundation. However, to reduce the offshore installation time, it is better to pre-assemble the turbine components in the port to the extent possible [31]. The unassembled and assembled turbine components are loaded to the appropriate vessels to be carried to the installation site.

3.2.2. Foundation installation

The foundation installation methods vary with the foundation type, as explained below [36]:

- Gravity-based foundations

These foundations use their weights to stand on the seabed. The weight of such foundations is usually more than 2500 tons. The construction of such a foundation is a time-consuming process, and it often starts a year before the installation. The installation of a wind farm composed of gravity-based foundations requires three principal types of equipment: (a) a large floating crane with a capacity of more than 2500 tons; (b) a crane barge, which can transport and store several foundations; and (c) a tugboat or several tugboats that tow the crane and barge to the installation site.

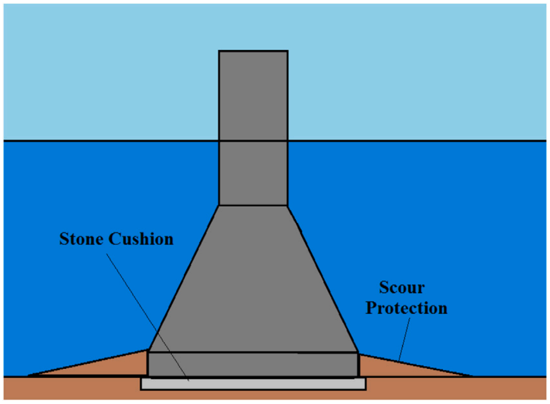

Fig. 7. MA gravity-based foundation, together with its stone cushion and scour protection.

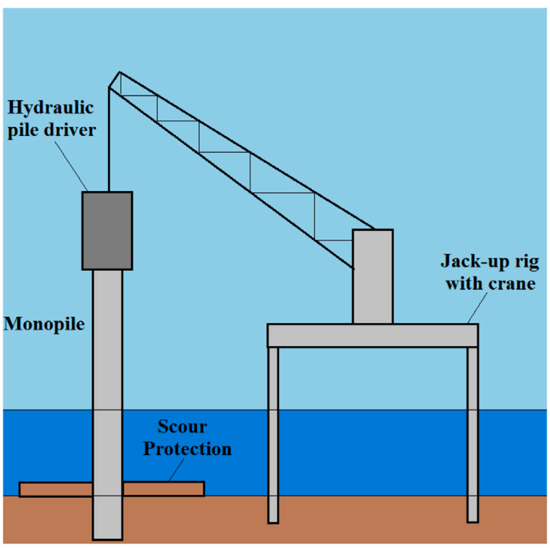

Fig. 8. The leading equipment used for the installation of a monopile foundation.

In addition, several other vessels such as dredgers and dumping vessels are used to prepare the seabed for the installation of the foundation [35]. Fig. 7 shows a gravity-based foundation, with its stone cushion and scour protection.

- Monopile foundations

Monopile has been the most commonly used foundation in the offshore wind turbine industry because of several reasons, such as the following [37]: (a) relatively easy and inexpensive design and construction, (b) efficient handling and storing, and (c) relatively simple installation and maintenance.

Fig. 8 illustrates the leading equipment used for the installation of a monopile foundation, including the installation vessel, which here is a jack-up large pile hammer for the pile-driving procedure (which can be hydraulic, diesel, and air operated), a pile-holding tool, and grouting equipment, which is used to cast the monopile to the transition part.

Additionally, scour protection vessels are used to install a stone layer constituting of small stones around the monopiles on the seabed to create a solid surface (see Fig. 8). In contrast to the gravity-based foundations, the seabed preparation is not needed, which reduces both the time and the expense of the installation.

- Jacket foundations

The lattice structure, which is the basis of jacket foundations, creates a strong and light construction capable of withstanding large loads. The idea behind using the jacket foundation is to reduce the cross-section area at the splash zone, where the waves are strong, thus decreasing the influence of the wave loads on the structure [34].

The installation of the jacket on the seabed is performed using four anchor piles on which the jacket will stand. At each corner, the jackets are equipped with sleeves, which are located accurately over the anchor piles. The structure-anchor piles' interface is then grouted [35].

The anchor piles are either suction or drilled/driven anchor piles [39]. The suction anchor piles have recently attracted much attention given their relatively high precision in installation [40]. The advantages of the suction piles over the drilled or driven piles are quicker and easier installation and removal during decommissioning [41].

- Tripod and tripile foundations

These foundations use several anchor piles to stand on the seabed. As with the jackets, they also have a relatively large footprint of about 25 m in 25 m. These foundations can be used for water depths ranging from 20 to 50 m [34]. It is also necessary to use scour protection for these foundations.

3.2.3. Transition piece installation

The transition piece is used to connect the monopile foundation to the turbine tower. This part is grouted to the top of the monopile over 6 to 8 m. The time needed to install the transition piece varies from 1 to 1.5 days. Note that the tripod-type foundation is already equipped with a transition piece. Additionally, the jackets and gravity-based structures do not need a transition piece [34,35].

3.2.4. Turbine installation

The components of a wind turbine such as tower, hub, nacelle, and blades can be partially or entirely assembled onshore and then transported to the offshore site. Accordingly, different assembly options can reduce or increase the installation and transportation process time.

A wind turbine component such as tower, hub, nacelle, and blades can be partially or entirely assembled onshore and then transported to the offshore site. Accordingly, different assembly options can reduce or increase the installation and transportation process time. Considering that the towers usually have two pieces, as shown in Fig. 9-a, a wind turbine has seven parts along with the nacelle, hub, and three blades.

Accordingly, as explained in [20,23,29,31], "bunny ear", shown in Fig. 9-b, is the configuration in which the hub, nacelle, and two blades are assembled in the port. The two pieces of the tower and the third blade are carried on the same vessel to the installation side. As there are four parts, four offshore lifts are required at the installation site. As shown in Fig. 9-c, the "bunny ear" configuration also can be used together with the assembled tower and the third blade. In this case, only three offshore lifts are required [20,31]. In the third alternative, shown in Fig. 9-d, the hub and three blades are assembled, and this assembly is carried to the installation site with the two pieces of the tower and nacelle. Thus, four offshore lifts are needed at the installation site [20,29,31].

As shown in Fig. 9-e, another possibility is to carry five pieces, including the assembled tower, hub and nacelle, and three blades to the installation local. Consequently, five offshore lifts are required at the installation site [20,31]. Fig. 9-f shows the last configuration in which only the hub and nacelle are assembled. The remaining five parts, including the two parts of the tower and three blades, are carried separately to the installation site requiring six offshore liftings [20,29, 31].

Note that, although the increase in the preassembled pieces decreases the installation time, it decreases the available space on the installation vessel simultaneously, which can reduce the efficiency of

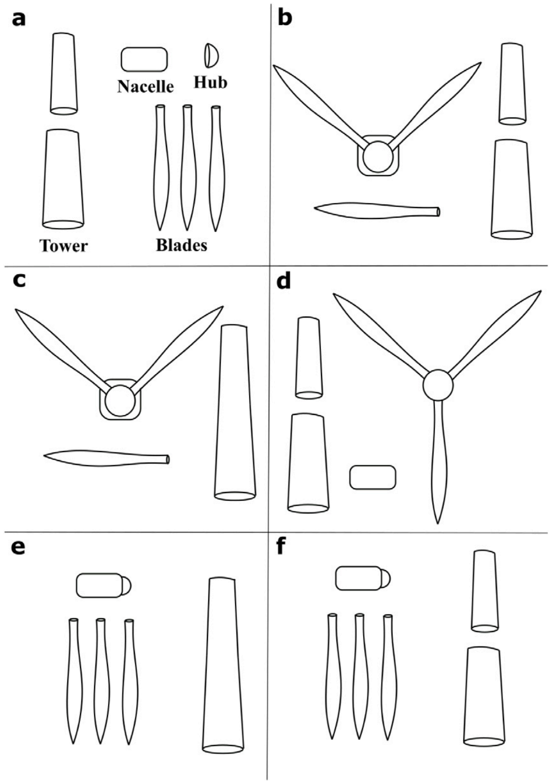

Fig. 9. Different assembly options for wind turbine installation.

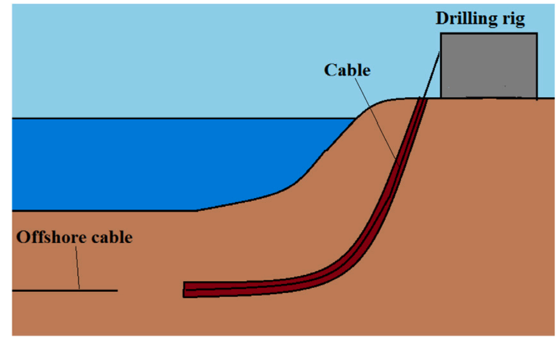

Fig. 10. Horizontal directional drilling (HDD).

the installation. Additionally, carrying the assembled parts is highly dependent on the sea states in which the transportation is performed. The choice of an appropriate preassembly method plays a critical role in reducing the time and, thus, the cost of transportation and installation. However, as indicated by [27], another important factor in reducing transportation and installation time is the learning rate of the workers carrying out the operations. Vis and Ursavas [29] suggests that the preassembly strategy must reduce the number of offshore lifts and at the same time provides the maximum amount of deck space available to carry more turbines.

Over recent years, the size of the wind turbine has increased significantly, which results in an increase in the size of the installation vessels, with a higher lifting capacity of the crane inside the installation vessels. Furthermore, by increasing the distance of the offshore site to port, larger installation vessels capable of carrying several wind turbine sets to the installation site are required [31].

3.2.5. Substation installation

Substations, which are built to collect all the energy generated by the wind turbines, are usually pre-assembled in the port and then transported to the installation site using a heavy lift vessel or jack-up vessel equipped with heavy lifting cranes with capacity from 900 tons to 3000 tons. For large wind farms, several substations are used. As a rule of thumb, for each 250 to 400 MW in installed capacity, one substation is installed [20].

3.2.6. Cable-laying operations

OWFs use two types of cables: array cables and export cables. Array cables are used to connect the turbines with one another and the substation, while the export cables are used to connect the substation to the onshore grid. A dedicated cable-laying vessel (CLV) or a barge is used for the installation of the cables [42]. Note that the installation of cables is usually performed by remotely operated vehicles (ROVs), and sonar is used to monitor the process [42].

It is common to bury the offshore cables to protect them from fishing gear and ship anchors. Three methods are used to bury the offshore cables under the seabed, including trenching, burial, and rock dumping [17,35].

The trenching and burial methods are expensive and time-consuming; however, they are the most preferred methods because of the high protection they provide for the cables. In the burial and trenching methods, the excavated soil is used to refill the trench. On the other hand, the rock-dumping method entails merely covering the cables under the rocks. To decrease the cost and time of cable-laying and to provide the minimum protection for the cables, the burial depth ranges from 1.5 m to 3 m [42].

Cable-laying is complex on the landfall, which is the transition region from the sea to the land. The landfall burial depths are usually 3 m to guarantee high protection for the cables against future erosion [35]. In areas where landfall construction cannot be carried out because of either environmental sensitiveness or large population, an alternative is the use of horizontal directional drilling (HDD) [43]. As shown in Fig. 10, HDD is a trenchless approach employed to install the cable underground.

Several tools can be used for cable burial; however, the proper tool's choice is determined by the capability of the tool to bury the cable to the predetermined depth in the seabed condition along the cable path. Note that increasing the burial depth increases the cable installation time irrespective of the tool that is used. The most common tools include cable plows, jet sledges and jet trenchers, and mechanical trenchers. A cable plow is a method in which a mechanical force is used to make a trench. It uses a simultaneous lay and burial method. It is also possible to use a particular grabber, and a loading system for post-lay burial. Jet sledges and jet trenchers are suitable in areas where the seabed has sand and clays. As the jet equipment is surface-fed, the maximum water depth for these tools is 30 m. Jet sledges perform the laying and burial simultaneously, while the jet trenchers bury the cable, which has already been laid on the seafloor. Mechanical trenchers use a wheel or a cutting chain to make a trench where the cable is laid and buried. These tools are used for the very tough seabed, and a support vessel is necessary. More details about these methods' advantages and disadvantages can be found in [17,42,44,45].

3.3. Operation and maintenance stage

The objective of the O&M is to make sure that the key performance indicators (KPIs) of the offshore wind turbine project are achieved [34]. KPIs mainly include financial profit, availability, and production. The definition of the O&M strategy must consider the proper tools and equipment, which include human resources and access vessels.

Generally, maintenance can be divided into two parts: regular (planned, scheduled) preventive maintenance and corrective (unplanned, unscheduled) maintenance, also known as "repairs" [34, 46–49]. The first type is determined by the annual service of a wind turbine, such as lubrication, and is performed to avoid failure in the components. The latter is determined by unforeseen turbine errors, where the intervention will be required mainly because of failures in the supervisory control and data acquisition system (SCADA).

An important factor is the daily rate of the vessels used in the O&M phase, which constitutes the main cost factor [50–53]. To access the wind turbine, a specific vessel called the crew transfer vessel (CTV) is required [34]. These vessels can carry up to twelve people on each trip. The vessel types used for this purpose vary from Monohull to Catamaran and SWATH. Another efficient way to access the wind turbine is the use of helicopters, which are remotely affected by weather conditions [46].

Note that for the transportation of large and heavy equipment (including gearbox, generator, nacelle, hub, and blades) to and from the wind turbines, the use of cranes or jack-up vessels is also required.

OWFs are also subject to various subsea risks, which require the wind farm O&M strategy to perform subsea inspections regularly [46]. These inspections include several items such as the protective coatings on the foundations and transition pieces, scour protections, grouted connections, and undersea cables [34]. Thus, different techniques such as ROV equipped with sonar systems and proper cameras were developed to inspect subsea structures [34].

3.4. Decommissioning stage

Decommissioning is the stage in which all the wind farm components–including the wind turbine, foundation, transition piece, cables, substation, and scour materials–are removed [7]. It is logical to have a detailed plan of where the wind farm is to go. Also, the approval of the installation of a wind farm requires the presentation of a detailed decommissioning plan by the developers [34]. Before the decommissioning, another option can also be exploited, which is the repowering [54,55]. This option has two types [7]: (a) partial repowering (refurbishment), in which minor components such as rotors, blades, and gearboxes, are replaced; and (b) full repowering, in which the turbines are replaced with larger turbines with larger capacity.

The importance of the decommissioning relies on the fact that the decommissioning project gives sustainability to the deployment of an OWF because it guarantees the restoration of the environment or offsetting for no mitigatable impacts.

So far, four OWF projects-including the Swedish 10 MW Yttre Stengrund, the Dutch 2 MW Lely, the Danish 5 MW Vindeby, and the most recent one, the Swedish 10.5 MW Utgrunden I-have already been decommissioned in 2015, 2016, 2017, and 2018, respectively [56]. It is significantly essential to determine what to do with the components of a wind farm after decommissioning. It may include reusing, recycling, or disposing of the decommissioned components.

Generally, there are two options for decommissioning: complete and partial removal. In partial decommissioning, certain components are left behind intentionally [7,55]. Based on international legal obligations, the full removal of wind farms is required after they have reached their life expectancy because of the hazards and obstacles they present for navigation and fishing [55]. This is the preferred option in Europe by countries that have already installed OWFs [12]. However, at the same time, there are provisions in the international decommissioning rules in which the complete removal of the OWF is dispensed if it poses high risks to the marine environment. In this regard, the partial removal of wind farms is put forward to protect the artificial reefs created by the marine biota in the wind farm installation site [57]. This is especially applied to the cables and scour protection, in which their complete removal can be detrimental to the new and stable ecosystem [55,58]. For instance, the partial decommissioning of oil platforms in the Gulf of Mexico, which began in the 1980s, has been shown to be more beneficial to the marine environment compared to their complete decommissioning [59,60].

As with the installation process, during the decommissioning stage, it is also beneficial to transport the structures as assembled as possible, which would definitely reduce offshore liftings [61]. The decommissioning phase has three main steps [7,58]: (a) the decommissioning planning to specify the operations to be performed, including the time and cost for each operation; (b) the removal of the structures; and (c) the monitoring of the recovery of the site and the destination where the wind farm components go.

4. Environmental analysis

Multiple direct and indirect effects on ecosystem processes and functions are expectedly due to OWF deployment [62]. The detailed description of activities related to OWFs –including installation, O&M, and decommissioning – allows identifying the stressors and environmental impacts on the receptors, considering different technologies.

Installation is the most critical stage in the environmental analysis of the OWFs [6,63]. However, other studies also showed activities associated with the O&M and decommissioning stages that also cause significant environmental impacts [16,63–75].

One of the difficulties of analyzing the environmental impacts of OWFs is the variety of terms for the definition of the specific impacts. It, consequently, hinders the identification of the receptors, stressors, and mitigation actions. Then, to improve this process, the impacts are gathered into general impact types considering the ecological levels and the spatial and temporal scales, as established in [18,62]. Such an approach was used by [17,72] to assess the impacts caused by submarine power cables and a specific OWF in Kattegat, Sweden, respectively. The relevant receptors and related stages corresponding to each impact type are identified and shown in Table 1. It gives a general vision of the environmental analysis addressed in detail in the following sections.

The most cited impacts include the “habitat disturbance”, representing the avoidance of fish, marine mammals, and birds, and the “mortality of individuals”, generally birds due to collision against the wind turbine structure (blades and tower), and the “physical damage” on fishes, marine mammals, and birds. Few studies, including [75–77], addressed the social or economic impacts. Snyder and Kaiser [64] highlights that the decrease of greenhouse gas emissions (GHG) has a significant effect on the regional and global scales. In general, as mentioned in [63], a key consideration is that all the cited impacts potentially can endanger the maintenance and protection of the ecological goods and services; thus, identifying and assessing the impacts associated with Ecosystem degradation should be prioritized. In 2006, Koller et al. [78] proposed a framework for assessing the significance of the social and environmental impacts of the OWFs. Boehlert and Gill [18] highlighted the necessity of developing sufficient knowledge for reaching an “impact evaluation level” rather than just defining the qualitative effects. Additionally, Vaissiere et al. [6] emphasized the importance of accurate environmental impact assessment for formulating suitable mitigation measures as biodiversity offsets on the marine environment. However, as also mentioned in [6], the consulted literature is not conclusive about the definition of scales of importance, significance, or magnitude of the environmental impacts of the OWFs, which are essentials for environmental impact assessment.

4.1. Environmental impacts of the installation stage

This section presents environmental impacts of the main activities of the installation of offshore wind turbines (OWTs). To the best of the authors’ knowledge, no work mentions the environmental impacts associated with transition piece installation. Additionally, the analysis omit the substation installation activities.

Table 1
Impact types according to relevant receptors and related deployment stage of an OWF.

Impact type	Relevant receptors	Related stage	Reference
Ecosystem degradation	Ecosystem: functions and services	Not specific	[73,78–81]
Habitat loss	Biodiversity: marine mammals, turtles and fish	Installation	[22,62,78,82]
Changes on habitat	Geophysical component: seabed-geomorphology	Decommissioning	[18,22,78]
Mortality of individuals or Population change	Biodiversity: marine mammals Biodiversity: birds and bats	Installation Operation	[12,22,78,82] [12,22,78,82]
Physical damage	Biodiversity: marine mammals Biodiversity: birds and bats	Installation Operation	[12,62,78] [12,62,78]
Habitat disturbance	Biodiversity: birds and bats	Operation	[16,62,78,82]
Negative modification of the environmental parameters	Social: landscape/seascape	Operation	[6,62,78]
Generation of negative social perception	Social: local community	Operation	[75–77]
Generation of positive social perception	Economic: fisheries	Operation	[75–77]
Positive modification of the environmental parameters	Geo-physical component: atmosphere	Operation	[62,83]
Creation of protected/conservation areas	Biodiversity: benthic flora and fauna	Operation	[16,62]
Enhancement of environmental/social parameters	Biodiversity: benthic flora and fauna	Decommissioning	[77,79–81,83]

4.1.1. Impacts during port logistics

Port logistics comprises several specific transportation activities; for instance, the transport of equipment and turbines is responsible for increasing the vessel traffic and generating loud noises, affecting other economic activities, as well as the biodiversity. Increased marine traffic affects activities such as fishery and the marine transport of commodities and other manufactured goods [84]. According to [64], loud noise might cause hearing damage and, in some cases, hearing loss in marine mammals. As reported in [71,72], increased vessel traffic might cause loud noises, for instance, due to the emitted noise by propeller cavitation (source level < 180 dB at 1 m distance). As mentioned in [73], background noise in the long term might cause cumulative effects in masking communicative abilities. Additionally, it reported a reduction of marine mammal populations due to the high density of sensitive resident marine mammals in Gulf of Lion OWF. Table 2 sorts the identified environmental impacts of activities associated with port logistics.

4.1.2. Impacts during foundation installation

The installation of the foundation is the most critical activity within the installation stage. It is mainly related to impacts on the submarine environment, including seabed morphology, biodiversity (benthic flora and fauna, fishes and marine mammals), and economic activities (principally fishery).

Some studies including [63,71,72] indicate pile driving as the most critical activity generating loud noise that may cause behavior or habitat disturbances. The sounds of pile driving might reach 228 dB in situ and 189 dB at 400 m away from the site [64]. Although these impacts are temporary and occur for a few days per turbine, their cumulativeness could cause hearing damage or loss on fishes and marine mammals [71,73,74]. As reported in [63,73], this activity might damage the porpoises' echolocation hearing. Additionally, Bailey et al. [71] showed concern about cumulative impacts caused by more than one wind farm on the population levels, especially the loud noise generated by pile driving that might affect marine mammals. Hammar et al. [72] found evidence related to the pile driving impacts on fishes, including a high risk for spawning cod, moderate for early recruits, and low for developed cod. Table 3 shows the installation activities and their environmental impacts.

As described in [63,72,85], the foundation installation also includes removing and modifying the seabed. Those activities may release particles, causing habitat disturbances as sediment dispersal and sedimentation, principally because of gravity foundations. These disturbances might affect submarine geomorphology and the benthic flora [64,67,71]. Despite this, they defined these disturbances as low-rated impacts. As mentioned in [63,74], other activities such as scour protection and cable trenching may cause habitat loss, for instance, benthic species, fishes, and turtles. However, Taormina et al. [17] affirmed that the affected areas are negligible compared to the project's total area.

4.1.3. Impacts during cable-laying installation

A few studies [17,18,86] address cable-laying operations in OWF installation. They showed that the techniques used for installing internal array connection cables and exporting cables (submarine energy transmission) might cause significant environmental impacts.

As described in Section 3.1, there are three cable-laying techniques: trenching, burial, and rock dumping. However, the environmental analyses in the literature use a generic term denominated cable trenching. In a trenching activity, specialized vessels or barges clean and excavate the seabed and then bury the cables about one meter into the seabed [72]. As mentioned in [63,87], it increases water turbidity and may cause sedimentation or modify superficial layers of the seabed. Regarding the biological resources, trenching activities may cause direct habitat loss, principally benthic flora and fauna. Simultaneously, Wilson et al. [63] stated that this impact is potentially unlikely to be significant compared to the total available habitat. Table 4 summarizes the environmental impacts of the cable-laying activity.

4.2. Environmental impacts of the operation and maintenance stage

The O&M stage is a less complicated stage but a long-term one, lasting about 20 to 30 years. According to [7,34], the O&M stage includes power generation (including the parked situation, when there is no power generation, caused by extreme conditions), submarine energy transmission, and maintenance. Fig. 11 depicts the overall impacts, including acoustic disturbance, habitat gain, electromagnetic fields and fisheries exclusion areas, caused by an OWF on the marine environment during its operation [85].

Table 2
Environmental impacts associated with the port logistics of an OWF.

Activity	Environmental aspect (stressor)	Environmental component factor (receptor)	Impacts (*: negative; **: positive)	Reference
Marine Transport (Foundations and turbines)	Vessel traffic	Economic Activity (Fishery and marine traffic)	Increased marine traffic*	[71]
	Loud noises	Biodiversity of marine mammals	Hearing damage/loss* Decreased population size*	[64,71–73] [64,71–74]
		Biodiversity of fish and turtles	Habitat disturbance* (mortality/avoidance)	[64,71–73]

Table 3
Relevant environmental impacts caused by foundation installation.

Activity	Environmental aspect (stressor)	Environmental component factor (receptor)	Impacts (*: negative; **: positive)	Reference
Pile-driving/drilling	Release/deposition of sediment particles	Physical component Seabed-morphology	Modification of seabed-morphology* (sediment structure)	[63]
Foundations (Gravity, piling, and drilling)	Removal of the seabed and sedimentation (disturbance of seabed)	Biodiversity of benthic flora	Habitat disturbance* (mortality/avoidance)	[63,73]
Pile-driving	Loud noises	Biodiversity of fish and turtles	Habitat disturbance* (avoidance/mortality)	[63,64,67,71–73]
	Loud noises (high frequency)	Biodiversity of marine mammals	Hearing damage/loss*	[63,64,71–73]
	Loud noises	Biodiversity of marine mammals	Decreased population*	[63,64,71–74]
Foundation installation	Installation of foundation structure	Biodiversity of benthic, and fish	Habitat loss* (direct occupation and scour protection)	[63]
Pile-driving	Loud noises	Economic activity fishery	Decreased fishery catch rate* (mortality/avoidance)	[64]

Table 4
Relevant environmental impacts caused by cable-laying activities.

Activity	Environmental aspect (stressor)	Environmental component factor (receptor)	Impacts (*: negative; **: positive)	Reference
Cable laying (trenching)	Release of sediment particles	Physical component Water quality	Increased turbidity*	[17,63]
		Physical component seabed-morphology	Modification of seabed-morphology* (sediment structure)	[63,72,73]
	Release of sediment particles (disturbance of seabed)	Biodiversity of benthic, fish and turtles, marine mammals	Habitat loss* (damage/mortality, avoidance, habitat disturbance)	[17,63,72,73]

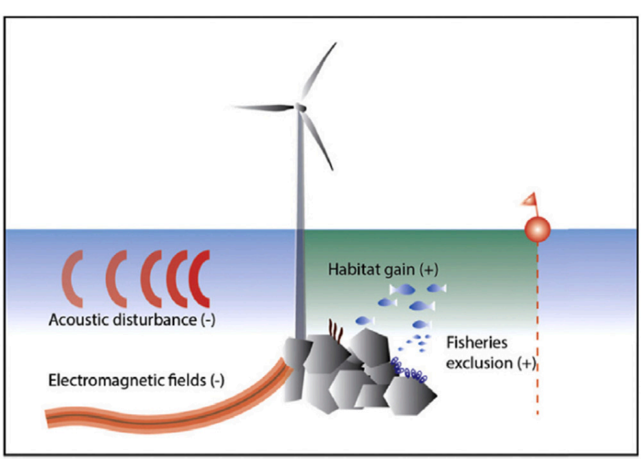

Fig. 11. Effects of the offshore wind turbine operation on the marine environment [85].

4.2.1. Impacts during energy generation

The literature review has allowed identifying at least eighteen impact cases shown in Tables 5 and 6. These impacts are related to the operation of an OWF. It is observed that, in some cases, various stressors (e.g., blades rotation and vessel traffic) can cause the same impact (e.g., avoidance due to habitat disturbance), affecting different environmental components or factors (e.g., marine mammals and fish). On the local scale, the OWT's presence might increase diversity because of the reef effect and create protected areas for benthic communities, fishes, and marine mammals because of the 3D complexity and hard substrates [63,64,88]. Additionally, more sustainable local fishery and improved fishery catch rates may occur as a consequence of increased diversity and protected areas. Decreasing energy prices may also affect economic activities given the addition of electricity to the national and local grids, being positive for customers and negative for developers [64].

Negative impacts vary from increasing the mortality of individuals to decreasing the population of birds due to the blades' rotation during energy generation as a cumulative impact of large OWFs, especially the long-lived species [16,63]. Noise and vibrations during energy generation are the stressors that may cause behavior disturbances (avoidance, breeding, and feeding changes) and hearing loss in fishes, marine mammals, and birds [73,75,82]. In extreme cases, this impact might lead to population reduction. However, as presented in various studies such as [65,74,75], these impacts are species-dependent and generally have low magnitude and significance.

Barrier and wake effect provoke behavior and habitat disturbances as a critical impact, with high significance, specifically, on marine mammals and migratory birds [62,75]. These effects may generate severe avoidance of typical migratory paths, causing extra energy demand and possibly increased individuals' mortality [16,57,63]. Additionally, in extreme cases, the wake effect's extension further than the OWF could cause habitat loss [70,89].

The scour protection of the foundations may cause the alteration of current flow/patterns and further changes to the seabed in the long term during the operation stage [63,88,101,102]. The presence of an OWF may generate land/seascape degradation, such as visibility or unique and historic site modifications, especially if installed near coastline [8,68,100]. As a result, it may modify the public perception represented as social reluctance and lower acceptance levels [67]. A literature review [75] concluded that the seascape is a relatively new concept required to be studied considering specific surveys for the visual impacts of offshore winds.

Additionally, an OWF may affect the economic activities of the locals, such as fishery because of the exclusion of fishing boats and the delimitation of no-fishing zones [67]. Tables 5 and 6 classify the associated environmental impacts considering two conditions of "power generation" and "no-power generation", which is related to the parked situation.

4.2.2. Impact during submarine energy transmission

Submarine transmission may affect the marine environment through transmission cables during the operational stage. As a positive impact, the transmission cables can act as an artificial reef, attracting marine life and increase diversity [75,88]. On the other hand, as described in [63], the electromagnetic field may cause behavioral disturbances such as avoidance or poor hunting performance in demersal and benthic fish species. As mentioned in [71,72], the impacts on elasmobranchs may be more severe than fish. Those impacts might lead to economic impacts such as decreasing the fishery catch rate caused by retarded migration or displacement accordingly [106,107]. Table 7 shows the specific environmental impact of the submarine transmission lines.

4.2.3. Impacts during maintenance

Maintenance activities occur during the operation stage. Lubricant and fuel spills–which cause water pollution and, consequently, a decrease of vulnerable species (i.e., early cod recruits)–are the most important impacts of the maintenance activities [72,73,75]. The introduction of alien species may affect marine mammals and fishes because of competition for feeding, reproduction, or breeding, causing local extinction. The disturbance over communities predated by birds might disturb bird populations. It might also cause fishery collapse, affecting the local communities that depend on it [108,109]. Table 8 sorts those impacts by activity.

4.3. Environmental impacts of the decommissioning stage

Until now, as explained in Section 3.4, only a few countries have decommissioned OWFs. Consequently, research on the environmental impacts of the decommissioning stage is scarce. As a consequence of the lack of experience and scientific research on the decommissioning of OWFs, developers should plan the decommissioning stage at the beginning of the project planning [110]. Additionally, the requirements of a decommissioning process are unique to each project. Different parameters–such as the size of the turbines, foundation type, site characteristics, or local market conditions–will affect the decommissioning procedures [79]. Table 9 shows two main impacts reported by [7,58].

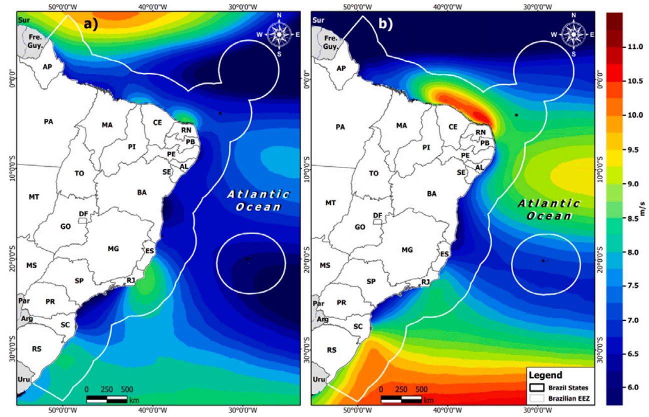

Fig. 12. Offshore wind potential along the Brazilian EEZ. Colors indicate average annual wind speed at hub height (z = 100): (a) austral summer season, and (b) austral winter season.

Finally, [55] proposed a renewables-to-reefs program, where they showed the environmental and economic benefits of partial removal as opposed to complete removal, especially if the habitat created on the remaining structures has conservation or commercial value. As presented in [111], substructures could become habitats for marine wildlife, such as fish or crustaceans.

5. Case study of Brazil

5.1. Offshore wind potential

The EPE estimated [5] a total offshore wind potential of about 11 TW within the Brazilian EEZ, with about 700 GW in regions of up to 50 m in water depth. The average annual wind speed of the Brazilian coastline, at the height of 100 m from the water's surface, is presented using hourly data from the atmospheric reanalysis through the ERA5 database from 1989 to 2019 [112]. Fig. 12a and b illustrate the results during the austral summer (December, January, and February) and winter season (June, July, and August), respectively. The results show the existence of three hotspots: the northeastern, southeastern and southern regions, with an average annual wind speed of more than 8 m/s.

As mentioned in [113,114], the State of Maranhão (MA), Piauí (PI), Ceará (CE), and Rio Grande do Norte (RN), each with a wide continental shelf, and relatively shallow water (lower than 50 m), are the most interesting regions in the northeast for OWF deployments. The south region also presents a significant offshore wind resource, especially along the coast of the Santa Catarina (SC) and Rio Grande do Sul (RS) states, as confirmed by [113–115]. In the southeast region, the states of Rio de Janeiro (RJ) and Espírito Santo (ES) present significant potential. Additionally, [114,116] showed the technical viability and possibility of complementing the energy demand of this region with OWE. [115] showed that the southeast offshore wind speed reaches up to an average of 9 m/s in areas with a water depth of between 50 m and 3000 m, where the implementation of fixed-bottom foundations, such as monopile and gravity based, is not feasible. It should be noted that 86% of the offshore wind resources of the southeast and south regions are located in water depths of more than 50 m [115].

5.2. Biologic resources

The characterization of the Brazilian coast's natural environment considering biological resources is highly relevant in the sense of identifying environmental vulnerability in the early planning stages of an offshore wind project. The most critical impacts affect marine

Table 5
Relevant environmental impacts caused by operation: power generation.

Activity	Environmental aspect (stressor)	Environmental component factor (receptor)	Impacts (*: negative; **: positive)	Reference
Power generation	Displacing fossil fuels	Physical component water stress	Decreased water** demand	[64]
		Physical component atmospheric	Decreased GHG emissions**	[64]
	Addition electricity to the grid	Economic activity electricity commercialization	Decreased energy price*/**	[64]
	Blades rotation	Biodiversity of birds and bats	Increased individual's mortality/decreased population size — decreased population* (collision against the blades)	[16,63,64,67,69,70,73–75,82,90–94]
	Noise	Biodiversity of marine mammals, birds, and bats	Decreased population size* (avoidance, disturbances change breeding and feeding behavior)	[64,72–75,82]
	Barrier effect	Biodiversity of birds	Behavior/habitat disturbance, Habitat loss* (avoidance, breeding, feeding)	[16,16,57,62,63,63,67,73–75,79,82,89,92,93,95–97,97–99]
	Wake effect	Biodiversity of birds and marine mammals	Habitat disturbance, Habitat loss* (avoidance)	[62,63,63,64,70,73–75,79,93,97–99]
	Noise (wind turbine)	Biodiversity of fish and marine mammals	Hearing loss*	[65,73,75]
		Biodiversity of fish	Behavior changes* (avoidance)	[65,73,75]
	Energy generation (situated in historic areas)	Social land/seascape	Land/seascape degradation*(visibility, unique, historical sites)	[64,66,67,75,100]
	Energy generation	Social Land/seascape	Public perception/social reluctance* (perception index %)	[66]

Table 6
Relevant environmental impacts caused by operation: power generation and no-power generation.

Activity	Environmental aspect (stressor)	Environmental component factor (receptor)	Impacts (*: negative; **: positive)	Reference
Power generation and no-power generation	Wind turbines installed (3D complexity: scour protection, foundation, wind turbine)	Biodiversity of benthic invertebrates, fish	Increased diversity** (reef effect)	[16,57,63,63,64,67,73–75,79,79,79,83,88,99,101,102]
	Exclusion of fishing boats/permanent no-fishing zones	Biodiversity of fish and marine mammals	Creation of protected areas**	[67,88,103]
	Exclusion of fishing boats/permanent no-fishing zones	Economic activity fishery	Increased sustainability of local fisheries**	[67,104]
	Foundation and scour protection presence	Economic activity fishery	Increased fishery catch rate**	[57,62,63,63,79,88,99,105]
	Foundation and scour protection presence	Biodiversity of marine mammals, birds	Alteration of community composition*/**	[63]
	Scour around the base of the turbine tower (disturbance of seabed)	Physical component seabed-morphology	Alteration of flow currents/patterns, further changes to the seabed*	[63,79,88,101,102]
	Exclusion of fishing boats/permanent no-fishing zones	Economic activity fishery	Generation of local opposition*	[67]

Table 7
Relevant environmental impacts caused during operation: submarine energy transmission.

Activity	Environmental aspect (stressor)	Environmental component factor (receptor)	Impacts (*: negative; **: positive)	Reference
Submarine energy transmission	Cable laying (presence)	Biodiversity of benthic fauna and flora	Increased diversity** (reef effect)	[17,88]
		Biodiversity of fish and marine mammals	Reserve effects**	[17]
	Electromagnetic field	Biodiversity of fish and turtles	Decreased population size* (poor hunting performance and feeding behavior)	[17,63]
		Biodiversity of fish and turtles	Reduction of local abundance* (mortality/avoidance of fish disturbance)	[17,63,71–73,75],
		Economic activity fishery, birds	Decreased fishery catch rate* (migration retardation, displacement)	[17,64,67,68,71,72,106,107]

Table 8
Relevant environmental impacts caused by Maintenance activities.

Activity	Environmental aspect (stressor)	Environmental component factor (receptor)	Impacts (*: negative; **: positive)	Reference
Maintenance	Lubricant spill	Biodiversity of fish	Water pollution* (e.g. decreased early cod recruits)	[72,73,75]
O&M Team and equipment transport	Introduction of alien species	Biodiversity of marine mammals, birds, and bats	Local extinctions and fishery collapses*	[88,108,109]

Table 9
Relevant environmental impacts caused during the decommissioning stage.

Activity	Environmental aspect (stressor)	Environmental component factor (receptor)	Impacts (*: negative; **: positive)	Reference
Green decommissioning (partial decommissioning)	Protection from bottom trawling	Biodiversity of benthic fauna and flora	Biodiversity enhancement**	[58]
Removal of the entire structure	Deeper excavation	Physical component seabed-morphology	Modification of seabed-morphology* (Sediment structure)	[7]

life, including benthic and pelagic communities. Additionally, based on experiences in environmental licensing, the marine protected areas and the presence of the O&G infrastructure, which is the largest energy supplier of Brazil [19], are strategic factors in the analysis of opportunities and conflicts associated with sea uses. Fig. 13 illustrates the distribution of biological resources, marine protected areas, and O&G industry presence throughout Brazil's EEZ, highlighting the regions of interest (hotspots) identified using the assessment of offshore wind resources (see Fig. 12).

5.2.1. Benthic biota

Benthic species play a vital role in the functioning of marine ecosystems, providing essential goods and services to these environments [119–121]. They are essential links in the food chain, serving as food for other organisms, mainly fish, including those of economic importance (human and industrial consumption) [122–124]. Additionally, they are important indicators of environmental quality. As shown in Fig. 13-a, they are widely distributed and abundant along the Brazilian coast, especially in the north, southeast and south regions, as well as the entire coast of the state of CE and a large part of RN state. They are widely used in the food and pharmaceutical industry, with emphasis on different types of algae, sponges, and crustaceans.

Corals and coral reefs constitute essential ecosystems and are considered the most diversified marine habitat in the world, with high economic importance, being sources of food and income for many communities. One in four marine species lives on reefs, including 65% of fish. The natural habitats of coral reefs are preserved through areas of environmental protection at the federal, state, and municipal levels, which are widely spread along the approximately 3000 km of the Brazilian coastline, from the MA state in the north to SC state in the south region (see Fig. 13-a) [125].

5.2.2. Pelagic biota

Part of the coastal resources, especially those in hard bottoms and those of the offshore platform and slope–including some deep-sea fish, shrimps, and crabs–consist of species of high economic value, which ensures the profitability of fisheries, even under low-density conditions [126]. The tropical biotas that are characterized by their low density and high species diversity are distributed along the northeast coastline, extended from Salvador in the Bahia state to the mouth of the Paraíba River in RJ state [127]. In general, the fishing chain in the northeast, including the states of Bahia (BA), Sergipe (SE), Alagoas (AL), Pernambuco (PE), Paraíba (PB), RN, CE and PI, is predominated by artisanal rather than industrial fishing. The main characteristics of these regions are the availability of species with high commercial value, decentralization of landings, use of poorly developed technology, and lack of infrastructure, from production to commercialization. Cape São Tomé in RJ state and Chuí in RS state are where a significant portion of Brazilian fisheries are concentrated, and whose stocks have shown unmistakable signs of overfishing [128].

Five of the seven types of sea turtles known in the world live along the Brazilian coast. Ocean beaches and islands are the main places for the spawning, shelter, food, and growth of these species. Their breeding habitats occur in the period between September and March [129], with the highest rate of spawning occurring in November [130]. The main species include the big-headed or yellow turtle (Caretta caretta), green turtle(Chelonia mydas), giant turtle, black or leather turtle (Dermochelys coriacea), turtle-de-comb (Eretmochelys imbricata), and small turtle (Lepidochelys olivacea) [130]. As illustrated in Fig. 13-b, they are distributed along the entire coastline.

In Brazil, the most common species of dolphins are the pink dolphin, porpoise, tucuxi, gray dolphin, bottlenose dolphin, and spinner dolphin, which are distributed from RS in the south to the state of Amapá (AP) in the north, where the occupied areas are extended from the nearshore, up to tens of kilometers away [131].

Cetaceans, principally humpback whales, visit the Brazilian coast annually, between July and November, for breeding. They tend to frequent shallow waters, preferably areas less than 500 m deep, with records of their occurrence from RS to Pará (PA) and with the highest concentration at Banco dos Abrolhos in the state of Bahia, between Southern Bahia and northern ES, where the continental shelf is considerably wide reaching, up to about 200 km [132].

Elasmobranchs include sharks and rays, are responsible for maintaining marine biodiversity, and are widely distributed in the marine and estuarine environments of the Brazilian coastline. These species take decades to recover from environmental degradation caused by human activities, including fishing. This is due to low growth rates, advanced reproductive age, long life, and the low number of young people [133]. These species use the Brazilian coast as habitats for breeding, nursery, and feeding as well as the migration of populations of different endemic species. In the north and northeast regions, they exist in areas with a water depth of up to 2000 m. They can be found in water depths of up to 1000 m in the southeast, and south regions, including the states of ES, RJ, São Paulo (SP), PA, SC, and RS.

Among the species recorded, we highlight the existence of the blue shark, hammerhead shark, Colombian catfish, crystal beak catfish, five species of coastal sharks, whale sharks, white sharks, and manta rays as well as the Carcharhinus galapagensis (supposedly extinct species) and Pristis spp. [133].

The presence of bird species is associated with seasonal movements at the local, regional, and intercontinental geographic scales, whose routes include specific breeding sites [134,135]. The habitats selected by migratory birds along their routes are related to feeding habits, the availability of resources, and species' foraging tactics, focusing

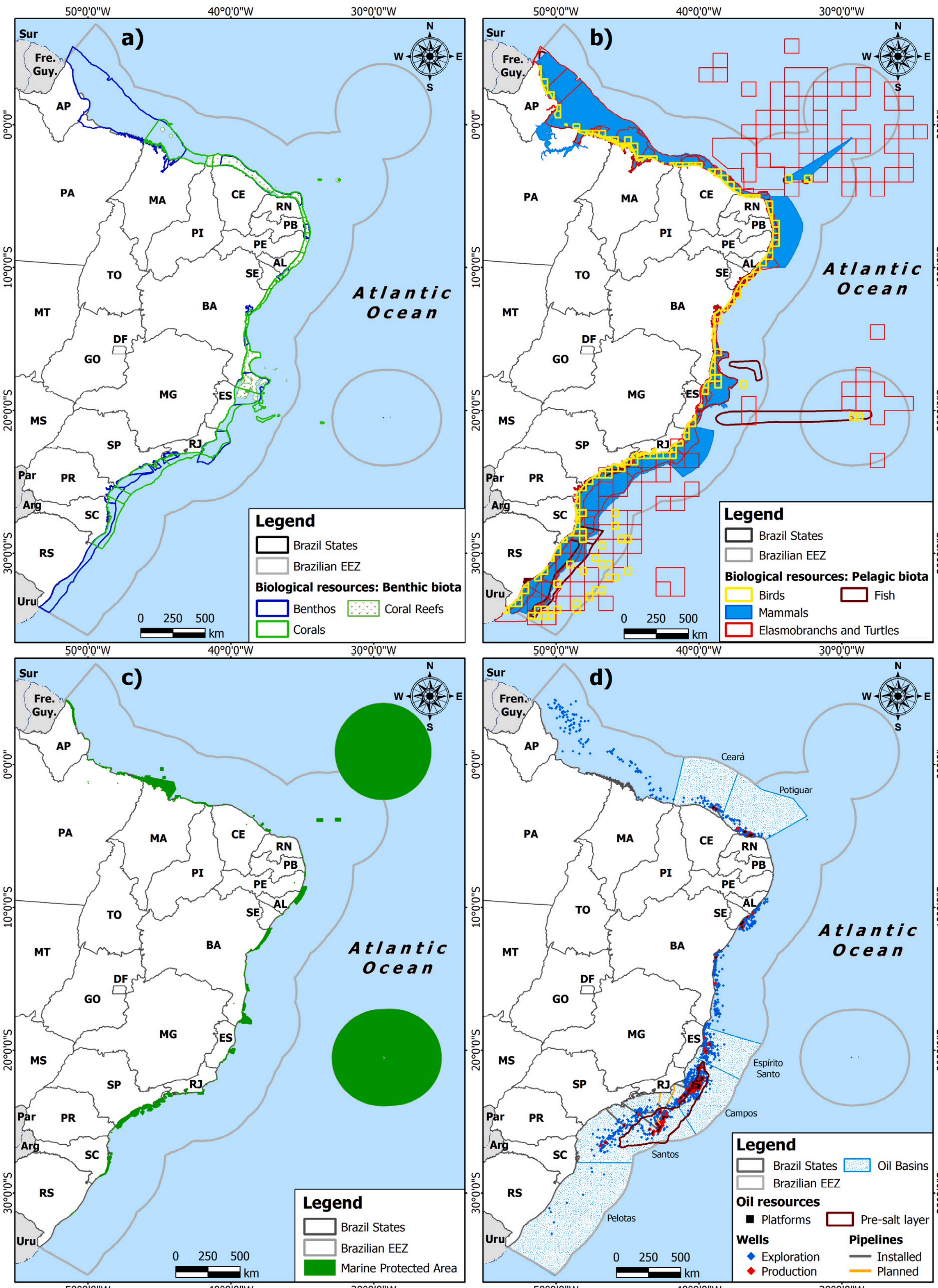

Fig. 13. (a) Biological resources: benthic biota, (b) Biological resources: pelagic biota, (c) Marine protected areas, and (d) O&G resources within the Brazilian EEZ [117,118].

on specific areas of fundamental importance for their conservation. Brazil is the second ranked country in terms of bird diversity, with 1901 documented species [136], being on the migratory route of many species that have their breeding sites in other countries (America, Greenland, areas in South America and Antarctica). There are records of the occurrence of more than one hundred species along the Brazilian coastline. Some of these species are residents, and others are migrants from the northern hemisphere and further south [137]. For instance, each year, by approaching the boreal autumn, about thirty species migrate to South America, reaching the Brazilian coast. These birds are concentrated in some specific places along the coastline of the states of CE, RN, PE, AL, BA, and RS. In general, these species stay in Brazil from September to May, depending on essential habitats for rest, seedlings, and feeding, as well as recovering energies spent on migration [138].

5.3. Marine protected areas

The Brazilian coastline, with 3.5 million km^2, includes different ecosystems such as coral reefs, dunes, mangroves, lagoons, estuaries, and swamps and more than 20% of the total species of the planet [139]. The conservation units, including integral protection units (IPU) and sustainable use units (SUU), form a set of protected natural areas to preserve this heritage and its biodiversity. The IPUs aims to protect nature, allowing only the indirect use of natural resources, excluding the consumption, collection, or damage to these resources. On the other hand, the SUUs make nature conservation compatible with the sustainable use of natural resources, allowing activities that involve its collection and use, practiced to protect the sustainability of renewable environmental resources and ecological processes.

The protected areas are associated with the various ecosystems that act as shelters and nurseries, benefiting migratory birds, mammals (humpback whales and dolphins), turtles (marine turtles), reefs (corals), elasmobranchs (rays and sharks), benthos, plankton, fish, and other species. The RJ and SP in the southeast, and the state of MA and a part of PA in the north, are the regions with the highest concentration of conservation units. Other protected areas are distributed along the coastline of the BA, SC, ES, PE, AL, CE, RN, and AP states (see Fig. 13-c).

5.4. Oil and gas presence

Brazil has abundant petroleum resources spread along with its territory, widely developed in exploration, production, and refining activities. O&G projects in offshore areas include platforms, wells and pipelines with refineries located onshore. According to the ANP [140], in January 2020, the total production of oil and natural gas in Brazil was approximately 4041 MMboe/d (millions of barrels of oil equivalent per day) [140]. This is about 47% of the internal energy supply of Brazil in 2018, as reported by the EPE [19]. Offshore production, with 96.9% of the oil and 80.8% of the natural gas, represents the largest amount of the total value.

As Fig. 13-d shows, in the southeastern region, Campos and Santos, located along the coastline of the RJ and SP are the most productive sedimentary basins with the highest offshore O&G potential in the country. They are located at a distance of 2 km to 487 km from the coast within a water depth of between 12 m and 2796 m. These basins concentrate most of the existing enterprises and their entire productive chain in Brazil. Their importance is intensified with the recent discovery of the pre-salt layer with immense offshore O&G resources located in the distance from 70 km to 577 km to the shore and a water depth range of between 70 m and 2740 m. In the northeastern region, the BA, CE, and RN states have significant areas of production, exploration, and refining (see Fig. 13-d). These areas are located at a distance of 0.5 km to 149 km from the coast, with a water depth range of between 3 m and 2890 m. In the south region, the presence of the O&G industry in the offshore areas is limited to the exploration sites, which are located at a distance from 20 km to 240 km of the coast with a water depth range of between 64 m and 1800 m [118,141].

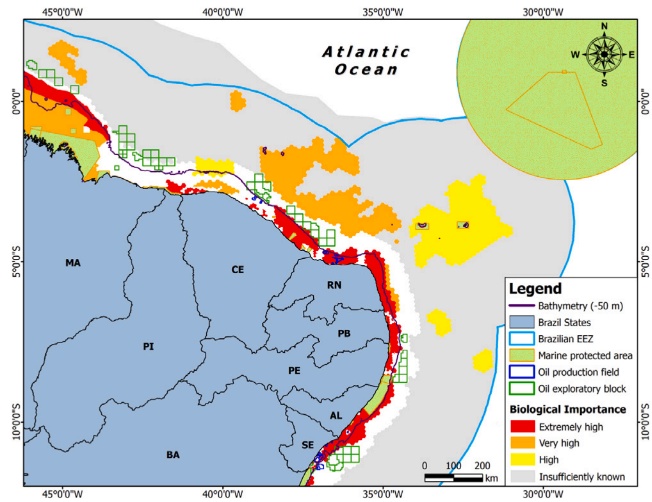

Fig. 14. Biological resource importance and presence of O&G industry along the Brazilian Northeast coastline [117,118,141–143].

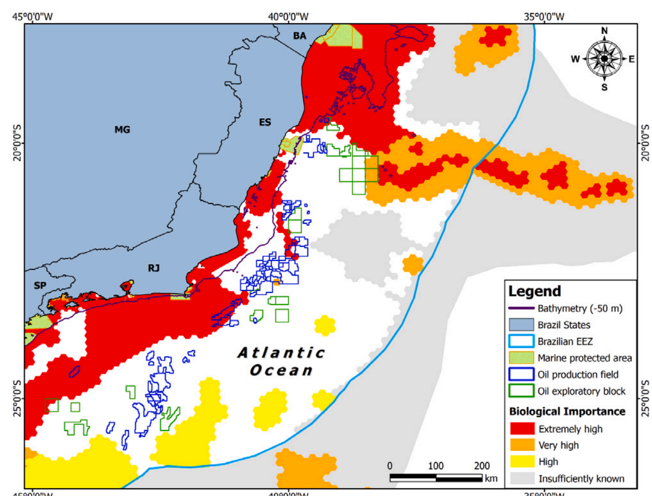

Fig. 15. Biological resource importance and presence of O&G industry along the Brazilian Southeast coastline [117,118,141–143].

5.5. Offshore wind hotspots status

Addressing the biological resources along the Brazilian coastline, as discussed in the previous section, reveals considerable gaps in information on the regional scale, as well as details at the local scale. Consequently, it makes unviable a confident diagnosis of the status of these resources along the coastline of the offshore wind regions of interest for accurate analyses of environmental impacts. Despite this, Figs. 14, 15, and 16 show the level of importance of the environmental parameters along the Brazilian coastline, based on the data presented by the Ministry of the Environment (MMA) of Brazil [142]. The report classified the environmental importance in the “extremely high”, “very high”, “high”, and “insufficiently known” areas. Additionally, the geospatial data associated with the marine protected areas and O&G exploration blocks and production fields are incorporated within the biological importance maps. The bathymetry isoline of 50 m is depicted to highlight the technical viability of the different types of offshore wind platforms.

In the northeast hotspot area (see Fig. 14) along the coastline of the RN, PI, and CE states, considerable regions of extremely high importance are located in water depths of up to 50 m. This implies

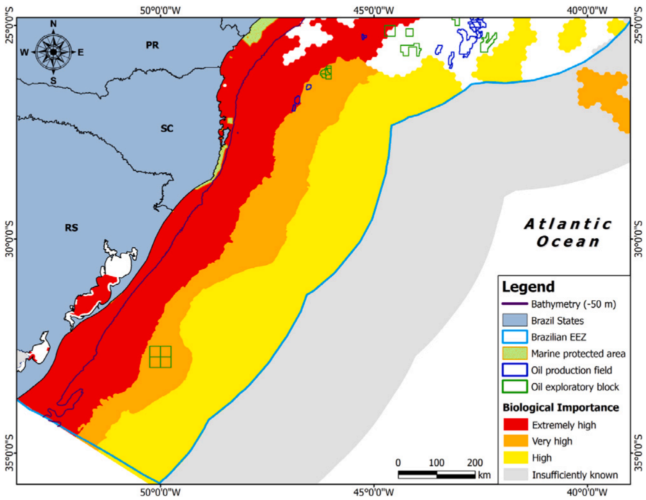

Fig. 16. Biological resource importance and presence of O&G industry along the Brazilian South coastline [117,118,141–143].

likely challenges regarding the environmental impacts of employing bottom-mounted foundations such as monopile and gravity based. As it shown a marine protected area occupied a significant part of the northern MA. The only intensive O&G production is observed in the north of RN, in a water depth of up to 50 m. However, most of the exploration blocks are located in water depths of more than 50 m.

Fig. 15 shows that the "extremely important" biologic resources extend along almost the whole coastline of the RJ and ES states. The concentration is on water depths lower than 50 m. However, in the case of RJ, these areas occupy the region with water depths of up to 2000 and 3000 m. Moreover, all the activities of O&G production and exploration are located in water depths of more than 50 m within areas that are not classified as having high, very high, and extremely high biological importance.

In the south region, Fig. 16 shows that the entire coastline of SC and RS have been identified as areas with an extremely high importance of biological resources. Additionally, marine protected areas occupy the southeast of SC within water depths of up to about 50 m. The O&G industry's presence is minimal in the south region representing some production activities, in the north of SC, and exploration blocks in the south of RS, all located in water depths of more than 50 m.

However, the accuracy of the delimitation of those areas and the information about the spatial distribution and temporal occurrence of the strategic ecosystems, including all biological resources and threatened species, are challenging. The seasonality of natural resources has a crucial role in the occurrence of environmental impacts. The temporal scales, which include the duration of an individual stressor, and whether it is persistent or intermittent, must be considered to attenuate or diminish the possible environmental impact.

The presence of the O&G infrastructure and facilities settled at sites with high offshore wind potential might cause sea use conflicts for installing OWFs on a large scale. On the other hand, existing anthropic activities associated with the O&G industry, environmental data, and environmental licensing experience might represent an opportunity to develop offshore wind projects in such areas. Another interesting possibility is the reuse of O&G infrastructure, which has been addressed by several studies, e.g., [144,145], avoiding its decommissioning or abandonment and, consequently, attenuating possible environmental impacts. Moreover, as addressed by [146,147], offshore rigs can be used to power oil recovery activities associated with the mature well providing a synergy between offshore wind and the O&G industry [148].

6. Conclusions and recommendations

This study performed a thorough review of the environmental impacts of offshore wind installation, O&M, and decommissioning, taking into account the main available papers in the literature as well as international and governmental reports. Additionally, a case study of Brazil was presented to address the environmental issues associated with the employment of offshore wind technology. The review employed a framework to identify the stressors, receptors, and positive and negative impacts related to the OWF activities.

It is observed that the seasonality of biological resources (e.g., the migrant birds, marine mammals, or sharks) and the time that the activity lasts are the key factors to prevent or mitigate environmental impacts. Additionally, an inadequate timing of the installation and decommissioning stages, which take several days, may cause the most significant impacts. Accordingly, the schedules for both stages should avoid the seasons of migration, reproduction, or nesting of vulnerable species. On the other hand, energy generation, which occurs during the operation stage and lasts for about 20 to 25 years, may cause negative impacts such as birds' mortality or population size decrease (by the rotation of the blades), especially when the wind farm is located on their migratory routes. In Brazil, in terms of available offshore wind energy, three hotspots are identified along the coastline of RN, CE, PI, and MA in the northeast, ES and RJ in the southeast, and SC and RS in the south region. The review of biological resources showed the existence of an enormous variety of endemic and migrant species sustaining ecosystems along the Brazilian coastline. However, there is a lack of detailed information on the regional and local scales that hinders the environmental impact assessment of OWFs. Areas with biological resources of extremely high importance are located along with the hotspot regions, especially within a water depth of up to 50 m, where fixed-bottom substructures are feasible. The presence of the O&G industry along the southeast and northeast regions of the coastline is a critical factor for the development of offshore wind projects in Brazil because of potential conflicts or restrictions that may occur between both industries. Spatial planning and environmental assessment studies must consider these issues carefully, in addition to the cumulative and synergistic impacts that these industries might cause together.

Considering the status of the Brazilian context, our recommendation is the establishment of an activity–stressor–receptor–impact relationship considering the mentioned factors, according to the characteristics of the project and the local environment. Note that a SEA performed at the initial planning stage of an OWF improves the sustainability of the project and facilitates the environmental licensing process. To achieve this goal, the following works are recommended: (a) defining the environmental parameters (including the physical, biological-ecosystemic, and social dimensions) and their measurement units and seasonability, which is crucial for accurate and suitable data collection campaigns; and (b) field data collection campaigns during the planning stage of the project, aiming to support the analysis of the specific activity–stressor–receptor–impact relationships for the project in the local environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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