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Geotechnical, Geological and Environmental Loads Considerations for Offshore Wind Turbine Foundations in Brazil

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ABSTRACT: The expansion of offshore wind energy reflects the increasing demand for low-carbon electricity generation. The structural reliability of offshore wind turbines depends fundamentally on the geotechnical performance of their foundations, which must withstand complex combinations of wind, wave, and current loading. In Brazil, offshore wind development remains at an early stage, and site-specific environmental and geotechnical conditions have not yet been comprehensively synthesized. This study presents a systematic literature review aimed at establishing a structured reference basis for the design and selection of offshore wind turbine foundations under Brazilian conditions. Emphasis is placed on the interaction between regional wind regimes and the geological and geotechnical characteristics of the continental shelf. The review is structured around four thematic domains: (i) the current status and regulatory framework of Brazil's offshore wind sector; (ii) environmental and ecological constraints; (iii) characterization and combination of environmental loads; and (iv) bathymetric, geological, and geotechnical conditions of prospective sites. A five-stage methodology was adopted, comprising literature identification, selection, screening, detailed evaluation, and synthesis of publications from 2000 to 2025. The study consolidates parameters relevant to preliminary foundation design, identifies critical knowledge gaps, and highlights engineering challenges associated with offshore wind deployment in Brazil. The results provide a structured technical basis for feasibility assessments and early-stage foundation design.

KEYWORDS: Offshore Foundations, Soil-Structure Interaction, Literature Review, Metocean Conditions.

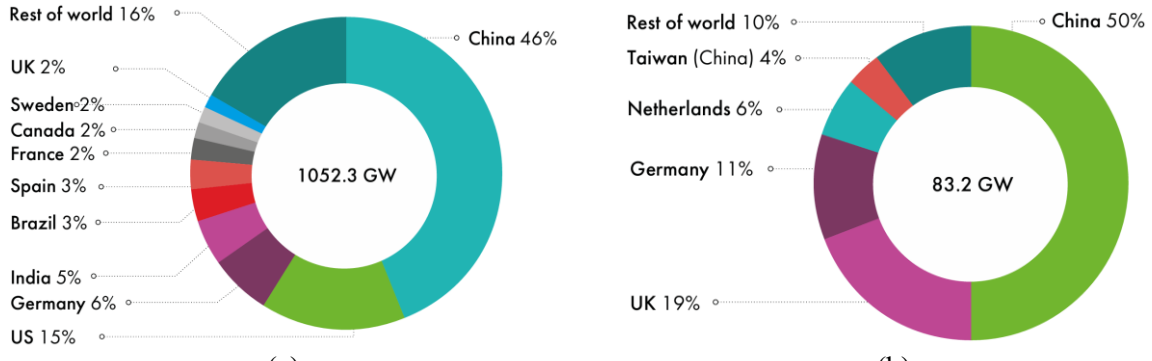
1 INTRODUCTION

Wind energy converts the kinetic energy of atmospheric flow into electrical power through wind turbines (Picolo, 2014; Almeida, 2024). It originates from differential solar heating of the Earth's surface, which generates large-scale air circulation (Dutra, 2008). Due to its low operational emissions, wind energy has become a central component of global decarbonization strategies (Silva, 2023). The electricity sector remains the largest contributor to energy-related greenhouse gas emissions (IEA, 2024), reinforcing the need for diversification toward renewable sources.

In Brazil, hydropower accounted for 56.1% of electricity generation in 2024 (EPE, 2025). Although global hydropower capacity is expected to grow (World Bank, 2024), increasing climate variability and hydrological uncertainty highlight the importance of complementary renewable sources. Offshore wind energy, in particular, offers significant diversification potential and may enhance system reliability when integrated with hydropower-dominated grids (World Bank, 2024).

Globally, installed wind capacity reached 1,136 GW in 2024, of which 83.2 GW corresponded to offshore installations (GWEC, 2025), presenting China, the United Kingdom, the United States, and Germany as energy powers (Fig. 1). The expansion of studies concerning potential deployment regions for offshore wind turbines and the optimization of their design enables wind energy market growth with exponential generation of clean energy and a gradual shift in the global energy sector, driving offshore wind trends across emerging markets. After 2020, new installations slowed due to a confluence of factors, including pandemic-induced supply chain disruptions, grid connection bottlenecks, and component failures. The delayed transition to deeper-water projects in key markets further tempered growth (GWEC, 2025). Despite these near-term constraints, long-term projections indicate continued expansion of offshore wind capacity, driven by persistent

energy security concerns - exacerbated by geopolitical tensions and high inflation - and firm decarbonization targets (GWEC, 2025).



(a) (b)

Figure 1. Contribution of leading countries to total installed wind capacity in 2024 for (a) onshore and (b) offshore installations (GWEC, 2025).

Brazil presents particularly favorable conditions for offshore wind development. The country has an extensive coastline, strong and persistent wind regimes that intensify with distance from shore (Ortiz and Kampel, 2011; Silva, 2023; Bottecchia, 2024), and proximity between potential sites and major port infrastructure (Bottecchia, 2024). Offshore installations reduce visual and acoustic impacts on coastal communities compared to onshore projects (Wu et al., 2019; Silva, 2023). Moreover, offshore wind demonstrates lower interannual variability compared to hydropower, positioning it as a strategic complement to Brazil's hydro-dominated grid (World Bank, 2024).

The successful implementation of offshore wind farms depends on reliable foundation systems capable of resisting combined environmental loading under site-specific soil conditions. Brazilian offshore geotechnical conditions are spatially heterogeneous and remain insufficiently characterized in the context of large-scale wind energy deployment. A structured synthesis of available environmental, geological, and geotechnical data is therefore required to support foundation selection and preliminary design.

This study presents a state-of-knowledge review of geotechnical, geological, and environmental loading considerations for offshore wind turbine foundation design under Brazilian conditions. The technical synthesis is developed through a systematic literature review structured in five stages: identification, selection, screening, detailed evaluation, and thematic synthesis of publications from 2000 to 2025. The review consolidates key engineering parameters, identifies persistent knowledge gaps, and outlines future research priorities. The resulting synthesis provides a structured technical reference to support feasibility studies and early-stage design of offshore wind foundations in Brazil.

2 BRAZIL'S OFFSHORE WIND MARKET

Although offshore wind farms are not yet operational in Brazil, the country has advanced its regulatory framework to enable future deployment. Offshore wind energy presents long-term potential as a complementary component of Brazil's electricity mix. Favorable wind resources, extensive maritime areas, and shallow continental shelf regions support the prospect of large-scale development.

2.1 Current scenario

As of 2025, 104 offshore wind projects were undergoing environmental licensing along the Brazilian coastline (Ibama, 2025). A relevant milestone was the issuance of the first preliminary environmental license for an offshore wind project. The license was granted for the Offshore Wind Turbine Testing Site in Areia Branca, Rio Grande do Norte. The project is coordinated by the National Service for Industrial Training of Rio Grande do Norte (Senai/RN) and implemented by the Senai Institute for Innovation in Renewable Energies (ISI-ER).

The testing site is located approximately 15-20 km offshore and includes the planned installation of two turbines with rated capacities of 8.5 MW and 16 MW (Senai/RN, 2025). The facility is intended to evaluate offshore wind technologies under Brazilian environmental and metocean conditions. It also contributes to the development of national technical expertise and specialized workforce capacity required for future commercial-scale projects.

According to the World Bank (2024) and GWEC (2025), Brazil's technical offshore wind generation potential is estimated at approximately 1,200 GW. Of this total, about 480 GW corresponds to fixed-bottom foundations in water depths up to 70 m, while approximately 748 GW is associated with floating foundation systems.

2.2 Regulatory framework

The establishment of a regulatory framework represents a necessary condition for offshore wind deployment in Brazil. In 2025, a comprehensive legal basis for offshore wind development was formalized.

National decarbonization policies were reinforced through legislation addressing renewable hydrogen and carbon markets. Law No. 14,948/24 established the National Policy for Renewable Hydrogen. Law No. 15,042/24 created the Brazilian Emissions Trading System, providing the basis for a regulated carbon market. Law No. 15,103/25 instituted the Energy Transition Acceleration Program to promote renewable energy expansion and industrial decarbonization.

Specific regulation for offshore wind was introduced through Law No. 15,097/2025. This legislation defines procedures for authorization and concession grants (GWEC, 2025) and establishes the legal basis for allocating marine areas for offshore energy projects. It also provides the regulatory structure required for conducting technical and environmental feasibility studies.

Despite these advances, the regulatory framework remains under implementation. Supplementary decrees are required to regulate area auctions and concession contracts (Agência Senado, 2025). In parallel, significant infrastructure challenges persist. Port facilities must be adapted to handle large offshore components, and transmission capacity expansion studies are necessary to support grid integration (Silva, 2023). The World Bank (2024) identifies priority upgrades for ports in each target region - Pecém (Northeast), Açu (Southeast), and Rio Grande (South) - to enable marshalling and assembly of large components. Transmission expansion and supply chain development for turbines exceeding 15 MW are equally critical for scenarios with higher installed capacity (World Bank, 2024). The development of construction, manufacturing, transport, and logistics capacity will therefore be essential for large-scale offshore wind deployment in Brazil (Silva, 2023).

3 REGIONAL CONSIDERATIONS

Environmental licensing for offshore wind projects requires comprehensive assessment of regional environmental and socio-economic impacts. Ecological and social constraints directly influence site feasibility, layout optimization, and preliminary engineering decisions. Offshore wind deployment may affect marine ecosystems, fisheries, navigation routes, and traditional coastal communities, requiring systematic integration of environmental and social variables during early-stage site screening (Gorayeb et al., 2022).

Impact minimization can be supported through pre-selection of high-potential areas based on exclusion and inclusion criteria derived from integrated technical, environmental, economic, and social analyses (Gorayeb et al., 2022). Projects submitted for licensing must comply with Ibama guidelines to ensure compatibility with biodiversity conservation and maritime activities.

From an engineering perspective, offshore wind foundation selection is governed by site-specific geographic, bathymetric, metocean, and geotechnical conditions. According to the World Bank (2024) macro-regional classification, the Northeast, Southeast, and South regions present the highest technical potential within Brazil's Exclusive Economic Zone. Estimated technically viable capacities are approximately 356 GW in the Northeast, 340 GW in the Southeast, and 660 GW in the South (World Bank, 2024).

The Northeast region includes nearshore areas accessible from the Port of Pecém, where moderate infrastructure upgrades are required. The Southeast region, centered on the Port of Açu, benefits from existing

offshore oil and gas infrastructure, which may facilitate logistical integration but requires coordination with dense maritime operations. In the South region, projects are supported by the Port of Rio Grande; however, portions of this area overlap with Ecologically or Biologically Significant Areas (EBSA), requiring enhanced environmental management and spatial planning (World Bank, 2024).

4 LOADS ON OFFSHORE WIND FOUNDATIONS

Offshore wind turbines operate as integrated structural systems. The rotor converts wind energy into mechanical power, which is transformed into electricity, while the tower elevates the rotor to optimize aerodynamic performance (García, 2004; Dutra, 2008; Picolo, 2014). The foundation transfers all applied loads safely to the supporting soil and must ensure stability and serviceability throughout the design life.

Offshore wind structures are subjected to complex loading regimes combining vertical and horizontal loads, cyclic actions, and dynamic effects (Şahin, 2004; Wu et al., 2019). Long-term structural performance requires resistance to fatigue and degradation under continuous environmental exposure (Castro, 2009; Picolo, 2014).

Loads acting on offshore wind foundations include the self-weight of the tower, nacelle, and rotor; aerodynamic forces generated by rotor thrust and torque; overturning moments at foundation level; cyclic loading from environmental actions; seismic forces where relevant (Milititsky, 2019); wind loads on the tower; and wave and current loads acting on the substructure (Fig. 2). Wind loads acting on large-diameter rotors generate significant overturning moments that increase with hub height and rotor diameter (Byrne and Houlsby, 2015). Offshore turbines are additionally subjected to hydrodynamic loading, which fundamentally distinguishes them from onshore configurations.

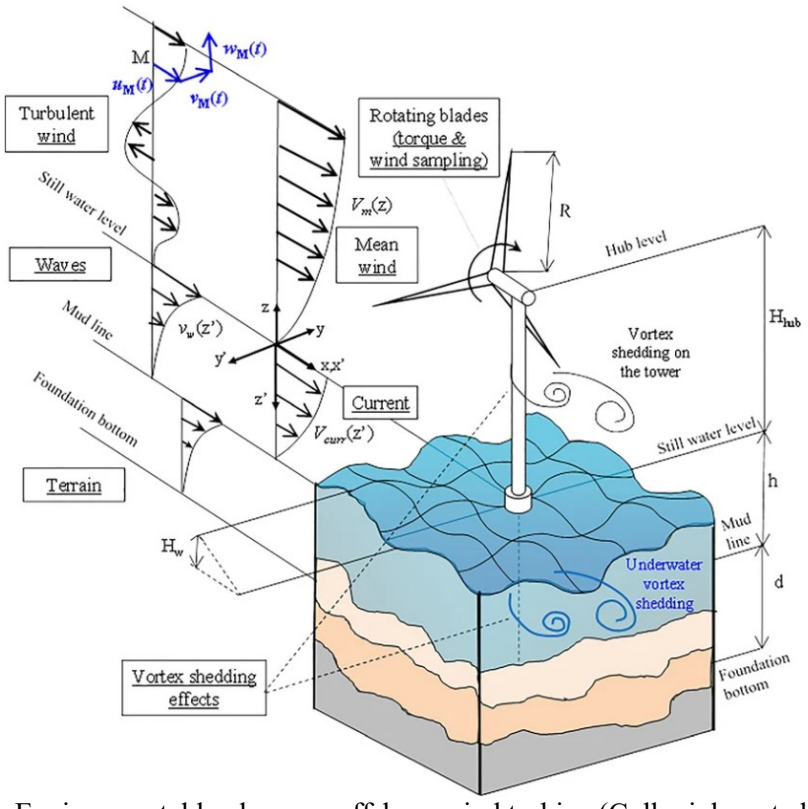


Figure 2. Environmental loads on an offshore wind turbine (Colherinhas et al., 2021).

Although preliminary analyses may reference standards originally developed for offshore oil and gas platforms, offshore wind turbines differ substantially in structural configuration and loading characteristics (Byrne and Houlsby, 2015). Load magnitudes vary according to turbine capacity, foundation type, and site-specific environmental conditions. Milititsky (2019) reported representative base load combinations for 120

m onshore towers, while Byrne and Houlsby (2015) presented typical load ranges for 3.5–5 MW offshore turbines (Fig. 3), providing reference values for preliminary assessments.

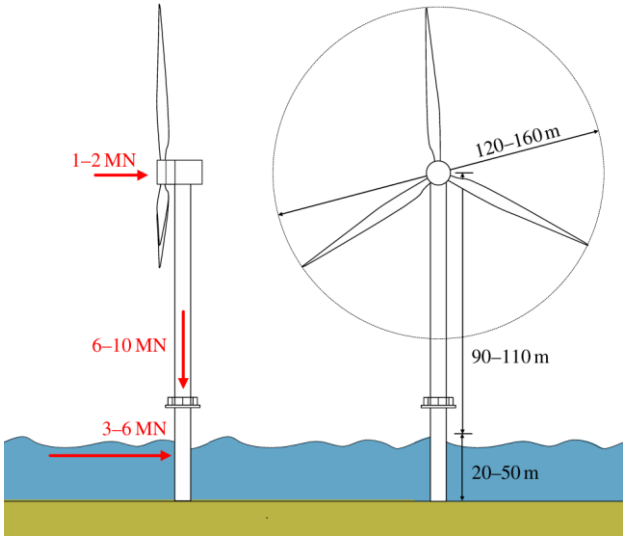


Figure 3. Typical loads magnitudes on offshore wind turbines (Byrne and Houlsby, 2015).

5 CHARACTERISTICS OF THE PROSPECTIVE SITES

Under the United Nations Convention on the Law of the Sea, the continental shelf corresponds to the natural prolongation of a coastal State's land territory to the outer edge of the continental margin or to 200 nautical miles from the baselines, with possible extension under Article 76 (United Nations, 2024). Geologically, the shelf extends from the shoreline to the shelf break at depths typically ranging from 100 to 200 m. Brazil's maritime jurisdiction, including the Blue Amazon, encompasses approximately 5.7 million km² (Agência Marinha de Notícias, 2023).

For offshore wind projects, geological, geotechnical, bathymetric, and wind conditions are primary determinants of foundation feasibility and design. Comprehensive site characterization is therefore essential for technically sound and economically viable development.

The Brazilian continental margin exhibits significant structural and stratigraphic variability associated with its tectonic evolution. Regional classifications have been proposed by Milani et al. (2000), Pontes and Asmus (2004), Vital et al. (2005, 2010), Goes and Ferreira (2017), Dias, Bastos, and Vital (2019), Morais et al. (2020), Alberoni et al. (2020), and Vital, Dias, and Bastos (2021). Pontes and Asmus (2004) divided the shelf into two principal provinces: a southeastern-eastern province dominated by carbonate and clastic sediments with terrigenous deposits such as shales and fine sandstones, and a northern province characterized by equatorial basins with carbonate lower sections and terrigenous shallow-platform facies.

Surface sediment mapping confirms marked regional variability. The Espírito Santo-Abrolhos shelf contains sandy deposits along the inner shelf and muddy sediments in depressions (Vital, Dias and Bastos, 2021). The Ceará shelf exhibits dunes, reefs, beachrocks, and incised valleys, with sand and gravel facies offshore and clay-rich deposits nearshore (Morais et al., 2020; Vital, Dias and Bastos, 2021). The Rio de Janeiro shelf includes carbonate ridges and terrigenous siliciclastic sands transitioning to carbonate domains offshore (Dias, Bastos and Vital, 2019). The Santa Catarina shelf is dominated by quartz sands, whereas the Rio Grande do Sul margin is characterized by terrigenous relict and palimpsest sediments (Dias, Bastos and Vital, 2019).

Bathymetric variability reflects tectonic evolution along the continental margin. Shelf break depths range from approximately 75 m in eastern sectors to 200 m along the meridional margin (Alberoni et al., 2020). These variations directly influence foundation typology selection, particularly the applicability limits of fixed-bottom systems and the potential need for floating solutions in deeper waters.

Wind conditions further reinforce offshore development potential and have direct implications for foundation design. According to the World Bank (2024), the Northeast region presents exceptional wind

conditions, with mean speeds of 7 to 10 m/s in shallow waters, making it suitable for fixed-bottom foundations. The Southeast region exhibits satisfactory potential for both fixed and floating projects, with average wind speeds of 8 m/s. The Southern region, with winds exceeding 8 m/s, offers favorable conditions for floating foundations in deeper waters. These values are compatible with commercial-scale offshore wind projects and directly affect aerodynamic load estimation, turbine selection, and ultimate foundation design requirements.

6 KNOWLEDGE GAPS AND RECOMMENDATIONS

The systematic review identified critical knowledge gaps that constrain the reliability of preliminary foundation design under Brazilian offshore conditions. Priority classification reflects the direct influence of each gap on foundation performance, structural safety, and long-term serviceability. Table 1 synthesizes the identified gaps by domain and strategic relevance.

Table 1. Summary of knowledge gaps affecting offshore wind foundation design in Brazil.

Domain	Knowledge Gap	Priority
Geotechnical	High-resolution characterization of soil cyclic behavior under combined wind and wave loading	High
Geological	Integration of regional sedimentological mapping with geotechnical design parameters	Medium
Environmental	Long-term monitoring data on soil-structure interaction under Brazilian metocean conditions	High
Regulatory	Clear technical criteria linking site-specific geotechnical parameters to foundation approval procedures	Medium
Floating systems	Geotechnical constraints for anchoring systems in deep-water Brazilian basins	High

Based on this synthesis, three priority actions are recommended to advance technically robust offshore wind foundation development in Brazil. First, the establishment of a national geotechnical database integrating data from offshore oil and gas exploration with high-resolution surveys in priority wind areas. Second, the implementation of long-term monitoring programs at pilot projects, such as the Areia Branca testing site, to quantify soil-structure interaction and cyclic degradation under representative metocean loading. These field programs should be integrated with complementary physical modeling investigations using geotechnical centrifuge tests. Third, the definition of technical criteria within forthcoming regulatory decrees that explicitly link foundation approval procedures to site-specific geotechnical and loading parameters.

These priorities align with the World Bank's roadmap for offshore wind in Brazil, which emphasizes the need for: (i) strategic energy planning with clear long-term targets; (ii) marine spatial planning to reconcile energy development with fisheries, biodiversity (notably in EBSA areas), and other maritime uses; (iii) port and transmission infrastructure upgrades; and (iv) supply chain development with phased local content requirements (World Bank, 2024).

Collectively, these actions directly address the identified gaps and strengthen the technical basis for large-scale offshore wind deployment in Brazil.

7 CONCLUSIONS

This study presented an integrated technical synthesis of environmental loading conditions, regulatory context, and geological and geotechnical variability relevant to offshore wind development in Brazil. The review consolidated key parameters influencing preliminary foundation feasibility, including aerodynamic and hydrodynamic loading regimes, sedimentological heterogeneity, bathymetric constraints, and regional wind intensity. The analysis highlights the technical importance of considering the interaction between water depth, soil stratigraphy, cyclic degradation behavior, and overturning moment demand under Brazilian offshore conditions.

Offshore wind energy has the potential to complement Brazil's hydropower-dominated electricity system due to its seasonal generation profile and comparatively lower interannual variability. In this context, its reliable integration into the national grid depends fundamentally on technically robust foundation systems capable of sustaining long-term cyclic loading under site-specific environmental conditions.

Substantial technical potential is distributed across the Northeast, Southeast, and South regions, with estimated capacities of 356 GW, 340 GW, and 660 GW, respectively (World Bank, 2024). However, realization of this potential depends on reducing uncertainty in soil behavior under combined wind and wave loading, refining marine spatial planning constraints - particularly in environmentally sensitive areas such as the South region's EBSA - and advancing high-resolution geotechnical investigation in priority areas. In deeper-water sectors exceeding the limits of fixed-bottom systems, evaluation of floating foundation anchoring performance in heterogeneous tropical sediments becomes critical.

The integrated synthesis developed herein consolidates the principal environmental, geological, and geotechnical constraints that condition offshore wind foundation feasibility under Brazilian conditions. Future research should prioritize high-resolution subsurface characterization, long-term monitoring of soil–structure interaction under cyclic loading, and quantitative assessment of floating system anchoring behavior. Advancing these technical foundations is essential to ensure structural reliability, serviceability, and fatigue resilience over the design life of offshore wind infrastructure in Brazil.

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