XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGENEERING

Optimizing Offshore Wind O&M Logistics in Brazil: A Techno-Economic MILP Model

Rafael Zorzetti Pereira[1], André Bergsten Mendes[1], Gustavo Roque da Silva Assi[1]

[1]*Polytechnic School, University of São Paulo (EP-USP)*
Av. Prof. Almeida Prado 128, 05508-070 São Paulo, Brazil
rafaelzorzetti@usp.br, andbergs@usp.br, g.assi@usp.br

Abstract. Brazil's offshore wind potential is largely unexplored and exceeds 1,200 GW (fixed and floating), according to a World Bank Group study, offering vast opportunities for renewable generation and for electrifying offshore oil-and-gas assets. Recent studies by the National Renewable Energy Laboratory (NREL) indicate that operations and maintenance (O&M) account for roughly 26% of the LCOE for fixed-bottom and 18% for floating offshore wind projects, highlighting the importance of logistical cost optimization for techno-economic viability.

We propose a mixed-integer linear programming (MILP) model that minimizes the combined fixed and variable costs of O&M while planning tasks over a multi-period horizon. The MILP optimizes two logistical choices: *(i)* whether, given the distance to shore, an offshore base (e.g., an Service Operation Vessel (SOV) or a fixed base) should be used or the wind farm should be serviced from an onshore port; and *(ii)* the optimal vessel fleet size and mix—i.e., the types and quantities of vessels required to execute a multi-period operations-and-preventive-maintenance plan at minimum total cost.

Uncertainty in input parameters, such as SOV capital costs and vessel day rates, is captured by integrating Monte Carlo sampling into the MILP loop. The model is implemented in Python and solved with Gurobi. In a case study with 40 turbines of 15 MW each, the model produces an optimized task schedule, an expected O&M cost component of LCOE between 3.33 and 4.46 USD/MWh (80% confidence), and identifies approximately 40 km from shore as the break-even distance at which an offshore base becomes cost-effective.

The model's modular structure supports extensions, including stochastic corrective maintenance, crane constraints (e.g., jack-up availability) and delay penalties, providing valuable insights for strategic O&M decision-making in Brazil's offshore wind sector.

Keywords: Offshore wind, O&M logistics, MILP, Monte Carlo simulation, LCOE

1 Introduction

Wind energy is widely recognized as one of the main sources of renewable energy in the world. In 2023, the total installed reached 1021 GW, of which 946 GW came from onshore installations, and 75 GW from offshore projects [1]. With an estimated annual growth of approximately 9% for the next five years, the offshore sector stands out, showing an even faster growth rate of around 27% per year. This progress is driven by global policies, such as those defined at COP28, which aim to triple the installed capacity of renewable energy by 2030. However, the economic feasibility and growth of these installations are intrinsically linked to the Levelized Cost of Energy (LCOE), a key metric for evaluating and comparing different energy technologies and resources.

Brazil ranks 6th in the world in onshore installed capacity, representing 3% of the global total. However, the country still does not contribute to the offshore segment, currently dominated by countries such as China, the United Kingdom, Germany, the Netherlands, and Denmark. Nevertheless, Brazil's offshore wind potential is significant, estimated at 1228 GW, with 480 GW located in shallow waters (distance from shore less than 50 meters) and 748 GW in deep-waters [2]. A roadmap of the offshore wind potential along the Brazilian coast was developed by the Energy Research Office (Empresa de Pesquisa Energética, EPE), an agency associated to the Ministry of Mines and Energy of Brazil. The exploitation of this potential presents economic, technological, and regulatory challenges, making LCOE an indispensable metric for comparing technological routes and assessing feasibility [3].

This article focuses on offshore floating wind farms and the logistical complexity of operation and maintenance, increasing with distance from shore, sea-state constraints and the large variety of support vessels. Opti-

mizing the fleet size and mix and the strategic location of support bases has a direct impact on operational and maintenance expenditures (OpEx) and, consequently, on the Levelized Cost of Energy (LCOE). According to the [4], OpEx is the fourth most sensitive component impacting the LCOE of offshore wind projects. Therefore, focus on strategies to reduce operation and maintenance (O&M) costs is essential and should be prioritized in techno-economic studies.

To address these challenges, this article formulates a mixed-integer linear programming (MILP) model that simultaneously determines optimal fleet size, type and allocation of vessels required to complete operation and maintenance planning, as well as the activation of either a fixed or mobile offshore base, aiming to minimize the total cost. The model is complemented by Monte Carlo simulations that account for parameter uncertainties, focusing on fleet costs and capacity factor, providing data to support strategic decisions on investment and operation and maintenance planning for offshore wind farms.

2 Methods

2.1 Problem Description

The problem addressed in this article involves key logistical decisions, such as whether to install a fixed offshore base and how to determine the optimal fleet size and mix, given a multi-period preventive operations and maintenance plan for offshore wind farms. As indicated in Figure 1, the scenario considers an offshore wind farm along the Brazilian coast, with logistical support provided by the onshore port and/or a fixed offshore base, both acting as operational hubs for maintenance vessels. In this article, the service operation vessel (SOV) is treated as a mobile offshore base, providing a flexible alternative to fixed installations for supporting maintenance operations.

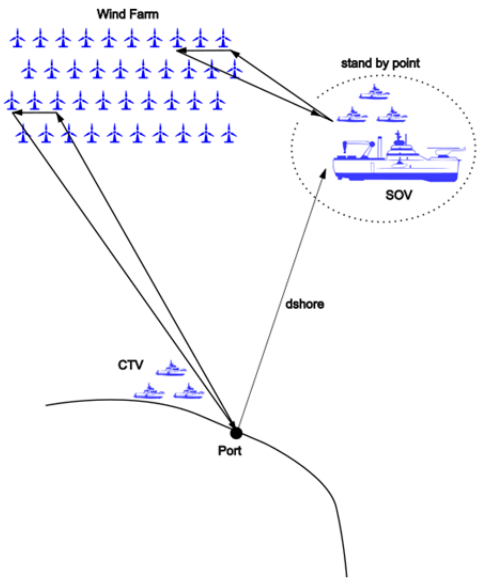


Figure 1. Schematic representation of the proposed problem.

Operational and preventive maintenance activities of offshore wind turbines is crucial for ensuring operational reliability and minimizing downtime, directly influencing LCOE. According to [4], OpEx costs constitute a substantial portion of the LCOE, significantly affecting the total life-cycle cost and economic feasibility of the project. Therefore, efficient logistical management of O&M activities, particularly concerning fleet size and composition choices as well as operational scheduling, plays a fundamental role in the economic viability of these projects. In Brazil, this challenge is even greater due to limited port infrastructure.

According to [5] a set of activities is required to ensure the long-term reliability and efficiency of wind farm assets, the main O&M activities include scheduled and unscheduled activities covering several critical systems: (i) electrical systems of the turbines and substations; (ii) mechanical systems within the turbines; (iii) structural inspections and repairs of foundations and substructures; and (iv) scheduled and unscheduled maintenance of all cable infrastructure, including array and export cables. Preventive maintenance tasks are performed regularly to anticipate failures and minimize downtime, while corrective maintenance addresses unexpected equipment faults.

In this context, the problem is formulated as a mixed-integer linear programming (MILP) model. The main objective is to minimize total costs associated with O&M, including fixed and variable costs of vessels and operational costs of logistical bases. The solution can determine:

- The optimal quantity and types of vessels to be deployed;
- Strategic activations and locations for offshore bases;
- Schedules for preventive and corrective maintenance;
- Optimized vessel routes to ensure efficient servicing of turbines.

Additionally, the problem explicitly considers significant uncertainties related to the main parameters, as such fixed and variable costs of the fleet, using Monte Carlo simulation techniques. This approach ensures that decisions made are robust against inherent variations in the offshore environment, reducing operational and financial risks associated with the project.

2.2 MILP

To capture the complexity of the offshore wind O&M logistics problem, the problem it is formulated as a mixed-integer linear programming (MILP) model. This approach allows for the joint optimization of vessel fleet size and mix, base selection, and maintenance scheduling, while rigorously respecting operational and resource constraints. The MILP formulation are described as follows.

Sets and indices

- $a \in A$ – operation and maintenance activities (electrical, mechanical, structural, etc.)
- $s, i, j \in S$ – wind turbines
- $p \in P$ – planning periods (day, week)
- $v \in V$ – vessels available (crew transfer vessel CTV, SOV, Helicopter, etc.)
- $w \in W$ – offshore support bases (fixed or SOV)
- $m \in M$ – onshore ports
- $c \in C$ – crew specialization (electricians, mechanics, welders, divers, etc.)
- $n \in N$ – nodes in the unified routing network, where $N = S \cup W \cup M$

Parameters

- C^V_{pv} – variable cost of operating vessel v in period p [USD/h]
- T_{ij} – travel time between nodes i and j [h]
- C^F_{pw} – fixed cost of operating offshore base w in period p [USD]
- C^F_{pv} – fixed cost of vessel v in period p [USD]
- R_{ac} – integer, number of resource units of specialization c required for activity a
- H_{vc} – integer, capacity of resource/specialization c available on vessel v
- T_{drop} – time required for crew transfer [h]
- T_p – total available time in period p [h]
- M – sufficiently large constant (Big-M)

Decision Variables

- z_{aspvw} – binary, 1 if activity a on turbine s in period p by vessel v from offshore base w, 0 otherwise
- z_{aspvm} – binary, 1 if activity a on turbine s in period p by vessel v from onshore port m, 0 otherwise
- z_{pw} – binary, 1 if offshore base w is active in period p, 0 otherwise
- x_{ijvp} – binary, equals 1 if vessel v travels from node i to node j in period p; 0 otherwise
- y_{ivp} – binary, 1 if vessel v visits node i in period p, 0 otherwise
- u_{ivp} – integer, position of node i in the route of vessel v in period p (Miller-Tucker-Zemlin [MTZ] variable for subtour elimination)
- w_{vp} – binary, 1 if vessel v is used in period p, 0 otherwise

Objective Function

$$\min Z = \sum_{p\in P}\sum_{v\in V}\sum_{i,j\in N\ i\neq j} C^V_{pv} T_{ij} x_{ijvp} \quad + \sum_{p\in P}\sum_{w\in W} C^F_{pw} z_{pw} \; + \sum_{p\in P}\sum_{v\in V} C^F_{pv} w_{vp} \tag{1}$$

Constraints

$$z_{aspvw} \leq z_{pw}, \quad \forall a, s, p, v, w \tag{2}$$

$$\sum_{p,v,w} z_{aspvw} + \sum_{p,v,m} z_{aspvm} = 1, \quad \forall a, s \tag{3}$$

$$\sum_{a,v,w} z_{aspvw} + \sum_{a,v,m} z_{aspvm} \leq 1, \quad \forall s, p \tag{4}$$

$$\sum_{a,s} \left(z_{aspvw} + z_{aspvm}\right) R_{ac} \leq H_{vc}, \quad \forall v, p, c \tag{5}$$

$$\sum_{i,j} T_{ij} x_{ijvp} + T_{drop} \sum_{s} y_{svp} \leq T_p, \quad \forall v, p \tag{6}$$

Constraints (2)–(6) establish the fundamental operational requirements of the offshore logistics system. Constraint (2) ensures that maintenance activities can only be assigned to an offshore base w if it is activated in period p. Constraint (3) guarantees complete coverage of maintenance tasks, requiring that each activity-turbine pair (a, s) is assigned exactly once, either from an offshore base or an onshore port. Constraint (4) prevents simultaneous operations at the same turbine within the same period. Constraint (5) enforces vessel resource capacity limits for each crew specialization, ensuring that the total demand does not exceed the available capacity H_{vc} of vessel v in any period. Finally, Constraint (6) ensures temporal feasibility by limiting the total travel time and stationary service time of each vessel to the period duration T_p.

$$\sum_{a,w} z_{aspvw} + \sum_{a,m} z_{aspvm} \leq y_{svp}, \quad \forall s, v, p \tag{7}$$

$$y_{svp} \leq \sum_{a,w} z_{aspvw} + \sum_{a,m} z_{aspvm}, \quad \forall s, v, p \tag{8}$$

$$\sum_{i \neq j} x_{ijvp} = \sum_{j \neq i} x_{jivp}, \quad \forall i, v, p \tag{9}$$

$$y_{jvp} = \sum_{i \neq j} x_{ijvp}, \quad \forall j, v, p \tag{10}$$

$$w_{vp} \geq z_{aspvw}, \quad w_{vp} \geq z_{aspvm}, \quad \forall a, s, p, v, w, m \tag{11}$$

$$\sum_{depot,j} x_{depot,j,v,p} = w_{vp}, \quad \forall v, p \tag{12}$$

$$\sum_{i \neq depot} x_{i,depot,v,p} \leq 1, \quad \forall \text{ depot } \in W \cup M, v, p \tag{13}$$

Constraints (7)–(13) integrate the assignment and routing components of the model. The constraint pair (7)–(8) establishes a one-to-one correspondence between activity assignments and turbine visits, ensuring that a vessel visits a turbine if and only if it has at least one maintenance activity assigned there. Constraint (9) enforces flow balance at each node for every vessel and period, maintaining route continuity. Constraint (10) connects visitation variables to routing arcs, indicating that a vessel visits a turbine if and only if it arrives there via some routing arc. Constraint (11) ensures that a vessel is marked as active whenever it is assigned any maintenance activity in a given period. Finally, Constraints (12) and (13) govern depot operations by requiring that each active vessel departs exactly once from a depot and may return at most once to each depot, thus accommodating both open and closed route configurations within the operational planning.

$$\sum_{a,s} z_{aspvw} \leq M \cdot \sum_{j \neq w} x_{w,j,v,p}, \quad \forall w, v, p \tag{14}$$

$$\sum_{a,s} z_{aspvm} \leq M \cdot \sum_{j \neq m'} x_{m',j,v,p}, \quad \forall m', v, p \tag{15}$$

$$x_{ijvp} = 0, \quad \forall i, j \in W \cup M, v, p, \; i \neq j \tag{16}$$

$$\sum_{i \neq j} \sum_{v} x_{ijvp} \leq 1, \quad \forall j \in S, p \tag{17}$$

$$u_{ivp} - u_{jvp} + Nx_{ijvp} \leq N - 1, \quad \forall i, j \in S, i \neq j, v, p \tag{18}$$

$$u_{dvp} = 0, \quad \forall d \in W \cup M, v, p \tag{19}$$

$$u_{ivp} \geq y_{ivp}, \quad \forall i \in S, v, p \tag{20}$$

Constraints (14)–(20) ensure route consistency and eliminate subtours within the optimization model. Constraints (14) and (15) enforce consistency between activity assignments and vessel departures, ensuring that if any activities are assigned to depart from a given port or offshore base, the vessel must have at least one outgoing arc from that depot in the routing network. Constraint (16) prohibits direct movements between depots (onshore ports or offshore bases), thus ensuring that vessels travel only between depots and turbines, not directly between depots themselves. Constraint (17) restricts each turbine to at most one visit per period across all vessels, thereby preventing redundant maintenance operations. Constraints (18)–(20) correspond to the Miller-Tucker-Zemlin (MTZ) subtour elimination formulation: Constraint (18) enforces a valid sequential order of turbine visits for each vessel, Constraint (19) initializes the depot positions to zero, and Constraint (20) activates the ordering variables for turbines that are actually visited. Collectively, these constraints guarantee that all vessel routes remain feasible and connected to their originating depots, with no subtours formed.

3 Results and Discussion

Three case studies were conducted for an offshore wind farm with of 40 $\times$ 15 MW turbines, located off the Ceará coast, Brazil. Input data are derived from official IBAMA maps for site locations [6], and technical and cost parameters taken from [7–9].

All mathematical programming problems were solved using Gurobi 12.0.3, executed on a workstation equipped with an Intel Core i7-8700 CPU, 6 cores, 12 threads, 64 GB of RAM, and running Microsoft Windows 11 64-bit. The computational setup and solver parameters were configured to accelerate the solution process and ensure feasible solutions with reasonable costs, especially for Case 3, which involved 1,000 Monte Carlo simulations.

3.1 Case 1 – Break-even Distance for Offshore Base Installation

Figure 2 illustrates the total life-cycle, 25 years, O&M cost (in thousand USD) as a function of the distance from shore to the wind farm. The results highlight the impact of higher variable costs for near-shore regions, where logistics rely exclusively on CTV (Crew Transfer Vessel) operations. Approximately 40 km, the installation of a permanently offshore SOV base is activated, introducing a important fixed cost component but significantly reducing variable logistics costs. This case is relevant to support strategic decisions for offshore base installation, given the Brazilian coastline's suitability for wind farm development at a wide range of distances from shore.

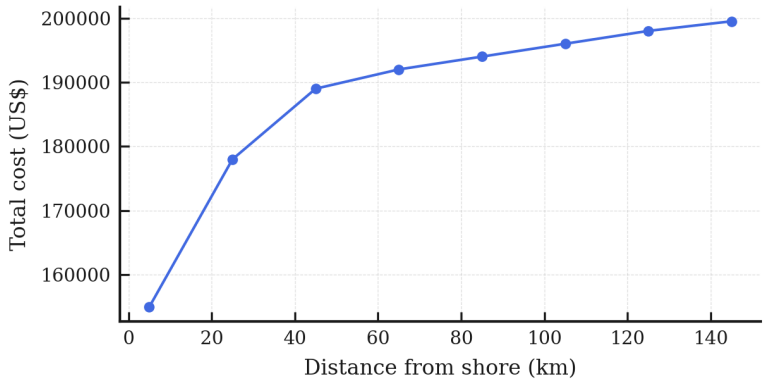


Figure 2. Break-even curve for offshore base installation: total O&M cost versus distance from shore.

3.2 Case 2 – Fleet Sizing and Routing Optimization

The optimal vessel fleet sizing and mix, and daily routing, were determined for a one-year planning horizon using the proposed MILP model. The full set of simulations required approximately three days to complete. The optimal solution prescribed a fleet configuration of eight CTVs and one SOV in order to execute all planned activities with minimal resource usage and maximal efficiency.

This model serves as a valuable decision-support tool, enabling both the determination of the optimal fleet size and mix, as well as the period-by-period planning of the best execution sequence for maintenance activities.

Figure 3 illustrates a representative excerpt of the wind farm, displaying the execution plan for a single day. The figure shows the spatial allocation of vessels and the scheduling of electrical, mechanical, foundation, and cable activities, highlighting how the MILP model coordinates vessel deployment and task sequencing within a given period.

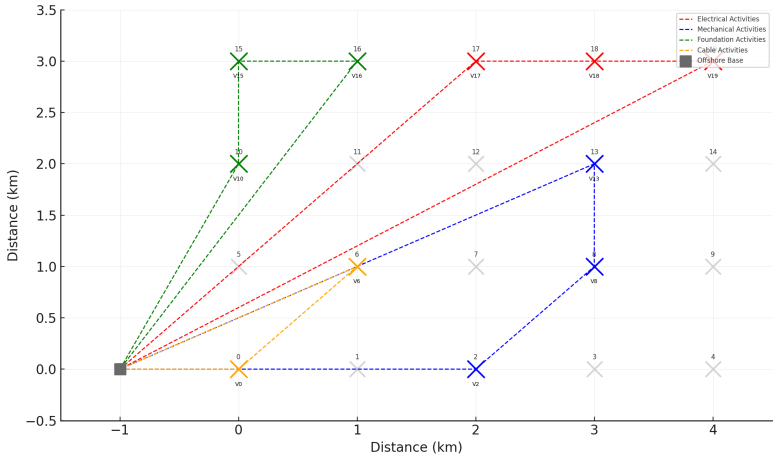


Figure 3. Example of optimized daily routing and vessel designation.

3.3 Case 3 – Monte Carlo Analysis of Fleet-related O&M LCOE

A dedicated Monte Carlo simulation was performed to quantify the uncertainty in the fleet-related O&M component of the LCOE, accounting for stochastic variations in costs parameters and wind farm capacity factor. Each scenario was evaluated using the MILP model to determine the annual fleet O&M cost and corresponding energy production.

The resulting empirical distribution of fleet-related O&M LCOE is shown in Figure 4. The histogram reveals a distribution with a long right tail. This long right tail is typical in O&M scenarios because rare but costly events can occur, such as unexpected equipment failures and extended turbine downtime, which significantly increase the total O&M cost in a small number of cases.

Sensitivity analysis indicates that increasing the daily SOV charter rate significantly shifts the distribution towards higher LCOE values, highlighting the strong impact of vessel contracting terms on O&M economics. In this study, the empirical distribution shows that, with 80% confidence, the fleet-related O&M LCOE lies between 3.33 and 4.46 USD/MWh. This probabilistic approach provides valuable insight for risk management and decision-making in offshore wind O&M planning.

4 Conclusions

This study presented an integrated optimization model capable of supporting strategic decision-making for offshore wind O&M logistics in deep-water scenarios off the Brazilian coast. By combining a MILP formulation with Monte Carlo simulation, the model effectively incorporates uncertainties inherent to parameters.

The proposed approach enables not only the optimal sizing and mix of vessel fleets, but also the period-by-period scheduling of maintenance activities, considering operational constraints. This level of planning detail supports cost-effective, directly addressing the logistical challenges typical of large-scale offshore wind farms.

By providing quantitative insights on break-even distances for offshore base installation and the risk envelope of O&M costs, the model delivers practical guidance for economic analysis and to support operators. Its flexibility

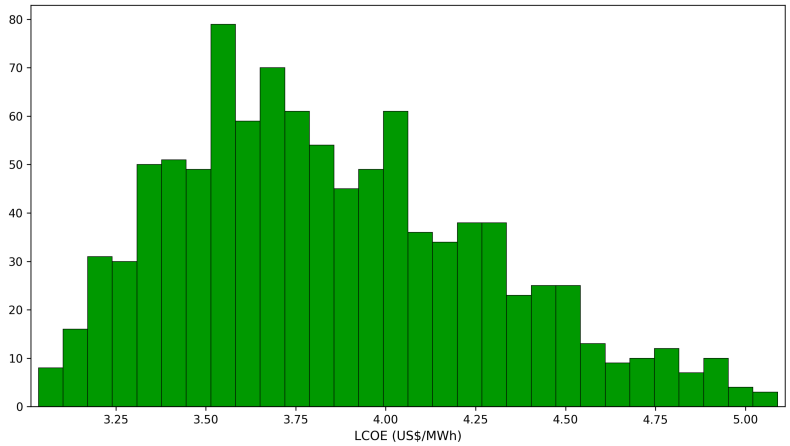


Figure 4. Empirical distribution of fleet-related O&M LCOE for the reference scenario (10,000 Monte Carlo samples).

and realism make it a valuable tool for the Brazilian context, where offshore wind projects may face widely varying site conditions and cost structures. The model can be adapted to address new scenarios by including sources of uncertainty and operational strategies, for example, stochastic events and the integration of climatic data, enabling more robust and weather-resilient offshore O&M planning.

The developed model is particularly relevant in the Brazilian context, where viable offshore wind farms span a broad range of distances from shore and operational conditions. Future research should integrate real climatic data, explore hybrid O&M strategies involving others vessels (helicopters and jack-up), and extend the modeling to multi-farm resource sharing.

Acknowledgments. The authors acknowledge the support of the OTIC Offshore Technology Innovation Center (EPUSP), the Fundação de Apoio à Universidade de São Paulo (FUSP), and the Graduate Program in Naval Engineering (PPGEN/EPUSP).

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Global Wind Energy Council. Global Wind Report 2024. Technical report, Global Wind Energy Council, Brussels, Belgium. ISBN: 978-9-46456-515-2, 2024.
[2] World Bank Group. Technical Potential for Offshore Wind in Brazil – Map: Going Global: Expanding Offshore Wind to Emerging Markets. Place: Washington, DC, 2020.
[3] T. V. B. Ferreira and e. t. d. EPE. Roadmap Eólica Offshore Brasil. Technical report, Empresa de Pesquisa Energética (EPE), Brasília, DF, Brasil, 2020.
[4] T. Stehly, P. Duffy, and D. Mulas Hernando. 2022 Cost of Wind Energy Review. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO, USA, 2023.
[5] J. Phillips, O. Fitch-Roy, P. Reynolds, and P. Gardner. A Guide to UK Offshore Wind Operations and Maintenance. Technical Report, The Crown Estate, 2013.
[6] Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA). Mapas de projetos em licenciamento - Complexos Eólicos Offshore, 2024.
[7] L. M. R. Silva, H. Li, and C. Guedes Soares. Service Operation Vessels Fleet Size and Mix Location Routing for the Maintenance of an Offshore Floating Wind Farm. *Journal of Marine Science and Engineering*, vol. 11, n. 3, pp. 664, 2023.
[8] M. Stålhane, H. Vefsnmo, E. E. Halvorsen-Weare, L. M. Hvattum, and L. M. Nonås. Vessel Fleet Optimization for Maintenance Operations at Offshore Wind Farms Under Uncertainty. *Energy Procedia*, vol. 94, pp. 357–366, 2016.
[9] Elin E. Halvorsen-Weare. Vessel Fleet Analysis for Maintenance Operations at Offshore Wind Farms. *Energy Procedia*, vol. 35, pp. 167–176. Publisher: Elsevier, 2013.