

Article

A Sustainability-Driven Approach to Early-Stage Offshore Vessel Design: A Case Study on Wind Farm Installation Vessels

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Abstract: This study presents a methodological framework for integrating LCA principles into the preliminary design phase of an offshore vessel. The framework is based on the case of a wind farm installation vessel (WTIV). The proposed approach diverges from traditional ship design by treating environmental impact as an important criterion and integrates the LCA into the early design stages, which is a novelty of the sustainability-driven ship design. On the basis of steps usually conducted in the preliminary ship design, a parametric study was conducted to evaluate the life cycle emissions associated with the shipbuilding, maintenance, operation, and dismantling phases. Ship characteristics such as displacement, lightship weight, and main dimensions were correlated with LCA factors, enabling the quantification of emissions at an early design stage with the use of the developed database and statistical regression models. Power demand estimation for different operational scenarios—free-running transit, dynamic positioning, and stationary installation—highlighted the significant contribution of offshore-specific vessel activities to life cycle emissions. The results demonstrate that the operational phases remain the most important contributors to overall emissions, mostly through CO₂ and NO_x production. However, emissions from shipbuilding, maintenance, and dismantling also play a critical role, justifying the need for early design interventions. Our findings highlight the need to integrate LCA into the design spiral for balanced sustainability, efficiency, and feasibility. This study provides a foundation for future research into multi-objective optimization models that incorporate LCA into offshore vessel design.



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Keywords: LCA methodology in ship design; wind turbine installation vessel; offshore ship preliminary design

1. Introduction

The objective of this study is to develop a comprehensive methodology for the preliminary design of offshore fleet vessels, taking into account all stages of the ship's life cycle. The proposed approach diverges from the traditional design problem framework, where design assumptions are typically based on performance metrics such as speed, deadweight, deck working area, or the number of TEUs. The unique operational characteristics of offshore vessels necessitate a specialized approach to the design problem. Unlike transport vessels, offshore specialized ships operate in varied cycles, requiring dynamic positioning, harsh-weather operation, emergency standby, and task-specific capabilities, such as wind farm installation. The distinct demands of these vessels must be carefully integrated into the design optimization to ensure both functional and environmental performance throughout their life cycle. A wind farm installation vessel (WTIV) for deploying turbines in

Poland's Baltic Sea EEZ was selected for the case study on integrating LCA into preliminary ship design.

In this chapter, we address the significance of the research and provide an overview of the current state of the field by organizing the literature review thematically into the following key areas relevant to the proposed methodology:

1. Application of life cycle assessment in ship design and construction—integration of LCA methodologies into the design and construction of ships, emphasizing its role in evaluating environmental impacts throughout a vessel's life cycle.
2. Consideration of the unique characteristics of offshore vessels in sustainability-focused design—specific operational and structural features of offshore vessels that must be accounted for in the design process, particularly in relation to sustainability objectives.
3. Review and analysis of critical calculation methods and the merits used currently for methodology formulation—various calculation techniques and models essential to the development of the proposed design methodology.

The types and fundamental structure of life cycle assessment methodologies applied to ships are analyzed in [1]. A framework for the LCA method is proposed, with the primary categories of environmental impact assessment discussed. Particular emphasis is placed on techniques commonly employed to minimize energy consumption and environmental impact across three key phases: ship construction, operation, and decommissioning. The need for modernization in the materials used during ship construction and scrapping processes is highlighted. Additionally, the hierarchy of solid waste management is presented [1]. The article provides a holistic overview of the LCA method; it does not specifically address its application to the ship design phase or early-stage design estimations. It outlines the key issues that should be considered when performing life cycle assessments of marine vessels. In [2], the ship is considered as a series of subsystems, with the hull and engine room identified as the most significant contributors to atmospheric pollutant emissions. This paper presents the results of LCA studies for processes identified throughout the ship's life cycle. Algorithms for the estimation of weld lengths during manufacturing and the emissions from zinc anodes were developed. The attention was given to evaluating the impact of the adopted assumptions and the uncertainty in the obtained results. This study focused on LCA assessments related specifically to the emission of selected atmospheric gases during the operational life cycle of transport vessels. The results were presented for a single ship type, a tanker.

It has been recognized that fuel consumption and the use of materials for manufacturing are the most important factors influencing the life cycle performance of a marine vessel [3]. The comparison of the environmental impacts of 25 investigated scenarios with different fuel consumption and light displacement tonnage was conducted. Since most of the gas emissions come from fuel combustion during the ship's operation phase, this study considered the Energy Efficiency Design Index (EEDI). The EEDI is a crucial component of the International Maritime Organization (IMO) regulations aimed at lowering the carbon intensity of the world fleet. The index requires that the amount of CO₂ emitted by a vessel per ton-mile of work (cargo transported) be set using a formula based on the technical design parameters for a given ship [4]. Its formulation, however, is based strictly on the basis of transportation principles, and it is not the best-matched instrument to assess emissions of offshore vessels that often do not carry out any transportation work.

One study [3] considered changing the EEDI by installing additional systems, such as solar energy systems. Adding additional systems would reduce fuel consumption but would increase the ship's displacement. As a consequence, emissions from the production, maintenance, and also operation phases may increase [3]. A Panamax bulk carrier was

chosen as a reference example. The conclusions of the article focus on two indicators, and one type of ship was considered during the research.

It is not an obvious task to apply the LCA method for the early design phases of a ship, especially formulated in a multicriteria decision-making process. An example can be found in [5]. A specific life cycle model was developed, and related metrics in shipbuilding design, supporting decision-making processes, manufacturing/assembly practices, and maintenance were defined. The model provides a common structure for life cycle assessment (LCA) and life cycle cost analysis (LCCA), including the way to retrieve and collect necessary data for the analysis, starting from the available project documentation and design models. Different design configurations for hulls and hatches of a luxury yacht have been analyzed using the proposed model.

In one study [6], a novel methodology, Process Chain Analysis (PCA), was proposed to enable a precise assessment of various factors influencing a vessel's emissions throughout its entire life cycle. The analysis results indicated that a speed of 12 knots represents the optimal solution for tankers in terms of emission efficiency. The developed method was prepared and validated for one type of transport ship.

The LCA method was applied to the decision-making process for optimal configurations of marine propulsion systems from the economic and environmental points of view [7]. Studies proved that the method can be useful for accelerating the life cycle analysis, which allows us to obtain a long-term view of the economic and environmental impacts of particular products or systems installed on ships. The method was used for the assessment of the configuration of propulsion systems.

Interesting conclusions concerning energy efficiency, which is one of the LCA method's measures, for offshore vessels were presented in [8]. Offshore vessels deal with time-sensitive logistics and sophisticated marine operations for high-value offshore oil and gas installations. Empirical findings showed that energy-efficient vessels perform worse in both rates and utilization. This reflects industry preferences for high-powered vessels to meet on-time operation requirements, making environmental considerations and energy efficiency secondary concerns [8]. These results show that there is a need to seek compromise solutions already at the early design stages of such vessels so that suboptimal technical approaches aimed at improving energy efficiency do not penalize the vessel's ability to perform its functions. A blended formulation between life cycle cost (LCC) and life cycle assessment (LCA) was developed and presented in [9] and was implemented and applied to a Ro-Ro passenger ship design process in order to verify and validate the method. A new holistic multi-objective design approach was taken for the optimization of arctic offshore supply vessels (OSVs) for cost- and eco-efficiency [10]. The approach was intended to be used in the conceptual design phase of an Arctic OSV. Environmental investigation of the bulk carrier type of the ship using emission- and energy-saving technologies was the subject of investigations in [11,12]. The importance of considering emissions not only during operation but also throughout the entire life cycle of the vessel, including construction, operation, and decommissioning phases, was emphasized in [13] by the presentation of greenhouse gas emissions from cargo ships and shipping activities.

The research by the authors of [14] focused on the life cycle environmental benefits of fully battery-powered ships compared to traditional marine diesel engines. The comparative analysis revealed that battery-powered vessels offer significant reductions in greenhouse gas emissions but are not always the best solution for propulsion systems. Similar conclusions were presented in [15]. This paper evaluated the viability, environmental impacts, and economic feasibility of different energy carriers for three vessels of different ship types: a RoPax ferry, a tanker, and a service vessel. The results showed that battery electric and compressed hydrogen options may not be viable for some ships due to

insufficient available onboard space for energy storage needed for the vessel's operational range [15]. Similarly, in [16,17], the issue of reducing CO₂ emissions through the use of alternative fuels, i.e., methanol and hydrogen, and their impact on the service operation vessels (SOVs) design process was presented, including the limitations related to the storage of these fuels, in particular hydrogen. Integration of multi-source maritime information to estimate ship exhaust emissions [18] under varying environmental conditions, such as wind, waves, and currents, provided a more nuanced understanding of how external factors influence emissions, which is crucial for developing accurate emission inventories and regulatory frameworks.

Life cycle assessment of marine propulsion systems, comparing the GHG emissions of various technologies and design variants can lead to the conclusion that different functional applications require individual approaches [19]. Through three case studies involving a platform supply vessel, chemical tanker, and express boat, conventional fuels and engines were examined, as well as emerging alternatives like ammonia and electrification using batteries and fuel cells. The three case studies reveal no single ideal propulsion system for reducing GHG emissions. Some systems may reduce emissions in one application but have drawbacks in others. The operational profile of a vessel is the decisive factor [19].

Manufacturing and recycling of ships are phases that involve significant emissions [20,21], although it is recognized that the operational phase has the greatest contribution [2]. A case study [20], comparing the environmental impacts of hand lay-up and vacuum infusion methods in yacht manufacturing, indicated that production methods significantly affect the overall environmental footprint of marine vessels, highlighting the importance of manufacturing choices in sustainability assessments. It was also confirmed that, if a ship is purposefully designed and manufactured for hull reuse, it would demonstrate a significant reduction in CO₂ emissions when two life cycles are under assessment. If it is required that a vessel's hull be designed for dismantling to improve reuse, the operation and maintenance schedule must ensure the value of the steel is retained, and the data must flow between key stakeholders on the quality of the steel [21].

A study on the LCA of steel processing [22] used in the ship recycling industry in Bangladesh revealed the environmental implications of steel production and recycling processes, emphasizing the need for sustainable practices in ship dismantling operations due to the other possible adverse impacts on the environment recognized by this study. Comprehensive life cycle impact assessment methodology, including all phases of a ship's existence, quantifying the potential environmental risk and creating an economic index [23], confirmed that almost all the environmental impact of a ship during its life cycle occurs in the operation stage. It was revealed that the primary environmental impact categories are acidification, global warming, resource consumption, and urban air pollution [23].

LCA methodology has been proposed as a tool for regulatory frameworks to improve the level of unwanted emissions in the marine industry. The work [24] examined the role of LCA as a complementary tool to regulatory measures aimed at improving shipping energy efficiency. The findings suggest that LCA can provide valuable insights that enhance regulatory frameworks, ultimately leading to better environmental outcomes in the shipping industry. The International Maritime Organization's (IMO) initiatives and standards for ship energy efficiency and their implications for the industry are being introduced to the industry. This activity was reviewed [25] regarding the effectiveness of these initiatives in promoting energy-efficient technologies and practices within the maritime sector. It was concluded, however [26], that more precise input data should be obtained to improve the methodology to develop generally accepted emission inventories for an effective environmental policy plan, and the importance of accurate emission assessments for effective environmental management in shipping was underscored [26].

The above overview of LCA methodologies applied to the maritime sector, ship design, and operation underscores the importance of integrating environmental considerations into the life cycle of marine vessels. However, a key limitation emerges from the current body of research—the application of LCA methodologies during the preliminary design stages remains underexplored. This refers particularly to specialized offshore vessels that exhibit distinct operational profiles compared to traditional cargo ships.

The studies reviewed emphasize that LCA is predominantly employed in post-design phases or operational assessments. While significant advancements have been made in evaluating emissions and energy efficiency (e.g., through tools like the Energy Efficiency Design Index (EEDI) [3,4]), these methodologies often fall short in addressing the unique requirements of offshore vessels. These vessels may often prioritize high-powered propulsion systems to meet time-sensitive logistical demands or environmental loads, where energy efficiency is not always a primary design consideration [8].

The potential for LCA to influence decision-making during early design is highlighted in studies [5,9,10]. However, the limited scope and application reflect a broader gap in the research: the systematic incorporation of LCA as a criterion alongside traditional design specifications such as performance, safety, and cost.

Integrating LCA into early design phases for offshore vessels offers the following advantages:

1. Early LCA considerations allow designers to identify and mitigate potential environmental impacts during the design phase rather than retroactively addressing them post-construction or during operation.
2. The manufacturing and recycling phases are significant contributors to a vessel's life cycle emissions [20,21]. Early-stage LCA can better inform material choices and construction solutions.
3. Offshore vessels often operate in challenging environments requiring specific design adaptations.
4. Incorporating LCA into multicriteria decision frameworks enables a holistic evaluation of trade-offs among environmental, economic, and operational metrics [9].

The rationale behind picking a wind farm offshore installation vessel for consideration is they represent a prime opportunity to implement LCA methodologies at early design stages. These vessels must reconcile operational efficiency with environmental sustainability, as they play a critical role in supporting the transition to renewable energy. Applying LCA in the preliminary design should hopefully help tackle offshore environmental challenges, balance energy efficiency with performance, and maintain operational effectiveness.

2. Materials and Methods

Ship design is an iterative process that translates requirements into an optimized vessel, meeting technical, regulatory, and economic goals. Usually, it is carried out by a so-called design spiral, representing its iterative nature. It emphasizes that ship design is not a linear progression but rather an evolving process where multiple aspects are revisited and refined iteratively. For the conceptual or initial design, the spiral contains such activities as functional definition, determination of main dimensions, preliminary weight assessment, power estimation, stability calculations, and vessel compartmentation. In this chapter, we present the methodology of such a design synthesis to identify initial LCA merits and to seek relations between the usual ship's technical characteristics, being the subject of design parametric studies.

Figure 1 provides a flowchart of the proposed methodology for the offshore vessel design process, including power estimation and life cycle analysis of the design.

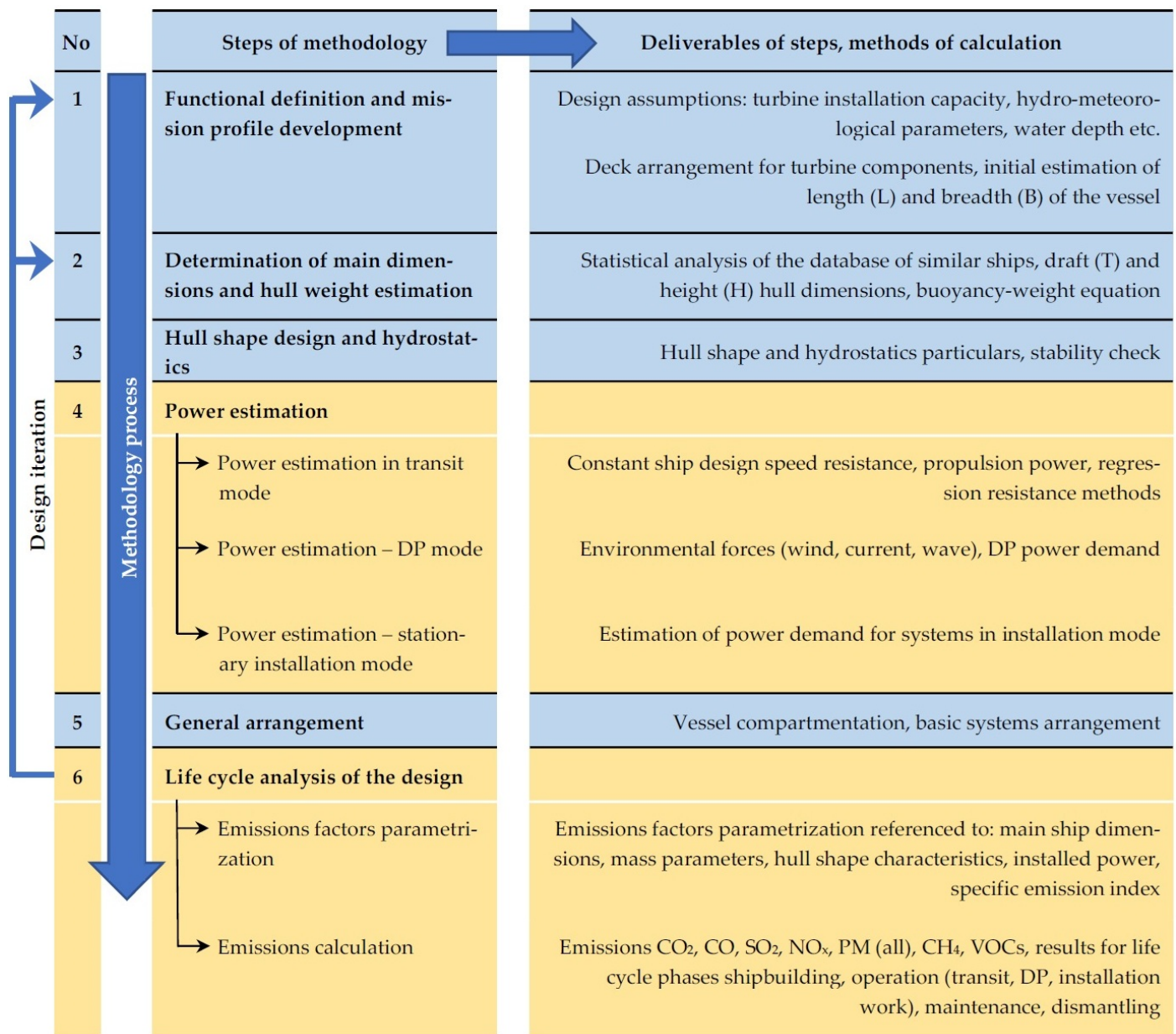


Figure 1. Scheme of the proposed methodology for the offshore vessel design process.

The above flowchart illustrates the methodology applied during the preliminary design of an offshore vessel. What distinguishes the proposed methodology from traditional design methods is, firstly, the inclusion in the life cycle assessment (LCA) analysis of all decisive phases of the vessel's life cycle; secondly, the parametrization of emission indicators relative to the main dimensions of the vessel, which facilitates subsequent design iterations aimed at improving environmental performance; and thirdly, the incorporation of operational modes in the preliminary design process, such as free transit, dynamic positioning (DP) operation, and installation work, as well as the separation of these modes for better analysis of operational scenarios in terms of environmental performance.

2.1. Functional Definition and Mission Profile Development

This section contains a detailed definition of the vessel's mission profile focusing on the size, weight, and transport requirements of wind turbine components. Operational parameters such as water depth, environmental conditions, and installation cycles are also analyzed.

With a growing demand for alternative energy, offshore wind turbines are increasing in size, requiring installation vessels with greater payload and lifting capacity. Larger turbines challenge onboard equipment, especially cranes handling heavier components. Cargo deck arrangement must also align with installation port capabilities. The designed vessel is assumed to operate in Polish offshore wind concessions in the Baltic Sea, a new challenge for local shipbuilding and port infrastructure. Figure 2 provides an overview of these concessions and key logistics hubs.

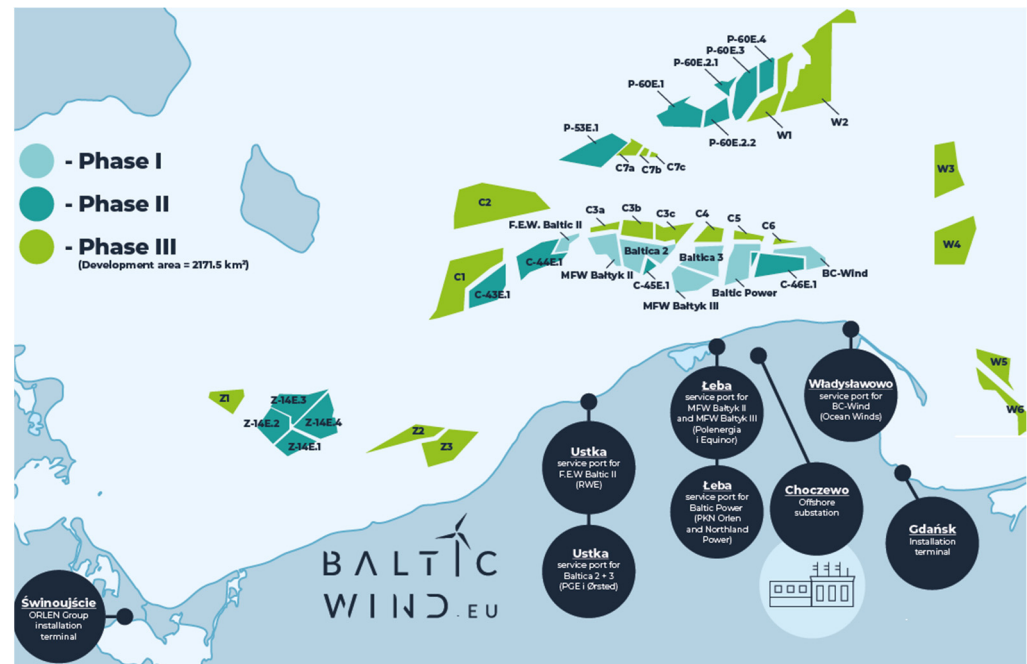


Figure 2. General overview of the Polish wind farm concessions and locations of most important logistics infrastructure, source: Report “Offshore Wind Energy Potential in Poland” published by the Polish Wind Energy Association, November 2022, [27].

The vessel’s concept is based on the following assumptions:

- Operating area: the Baltic Sea, the Polish offshore wind energy concession zones.
- Vessel function: transportation and installation of wind turbines.
- Vessel type: self-elevating platform (jack-up vessel).
- Turbine capacity: minimum of 4 sets (tower, nacelle, rotor blades), up to 6 sets.
- Water depth: up to 60 m, vessel transitional speed—12 kts.
- Boundary operational environmental conditions (worst working scenario): wind speed $V_A = 10$ m/s, current speed $V_C = 1$ m/s, wave height $H_S = 4$ m.

The functional analysis of the designed vessel and selection of its main dimensions can be executed when the assumptions are defined. For this purpose, the analysis of similar vessels is considered important. It enables the assessment of existing ships with functional and qualitative characteristics comparable to the vessel under design. The analysis of similar solutions is best conducted by compiling a list of comparable vessels and creating a database.

Vessels designed for offshore wind turbine installation are characterized by large area-based cargo spaces, allowing the transportation and installation of multiple turbine sets during a single voyage and relatively low usage of displacement by the payload. These vessels are often self-elevating (jack-up units), enabling them to perform installation tasks without the need for additional floating cranes. Precise positioning of jack-up legs is achieved using a dynamic positioning (DP) system. A critical piece of equipment is the crane, distinguished by its height and lifting capacity. It is used for turbine installation on

wind farms and, in the absence of appropriate cranes at the installation port, for transferring turbine components onto the vessel's deck. The development of wind energy has driven demand for larger cargo spaces and increased the lifting capacities of cranes installed on such vessels.

The selection of similar vessels for database creation in the design process is based on the parameters of the project's initial assumptions. For the vessel being designed, one key assumption is the minimum number of turbine sets to be transported, which must be at least four. Vessels included in the database should represent a comparable technological generation. The selection of similar vessels for database creation in the design process is based on the parameters defined in the project assumptions. The vessels included in the list should represent a similar technological generation. With the rapid technological advancements in wind turbines, the capacity and size of turbines have increased, necessitating the development of larger and more capable vessels for their installation.

The compiled dataset includes 21 vessels, most of which have been constructed, while a few are in the final design phase. The data were extracted from the information presented in [28–36]. The list is divided into three sections:

1. First section: includes basic geometric parameters and their statistical relationships, along with information on vessel speed, dynamic positioning (DP) system class, and maximum crew capacity.
2. Second section: provides details on the energy system of selected vessels, the power of the ship's power plant, as well as the number and capacity of thrusters and bow thrusters.
3. Third section: contains information on cargo capacity, the equipment used for its installation, and the lifting operations required for jack-up functionality.

Not all needed data were available and not all technical characteristics could be used, e.g., for the determination of statistical assessment for all ships. The most important technical characteristics of selected ships from the database are presented in Table 1. A database of similar vessels is crucial at this stage for utilizing statistical relationships, such as determining the main dimensions.

Table 1. Selected basic design parameters of the similar ships in the list [28–36].

No	Name	Year Built	LOA [m]	B/T	L/B	H/T	B [m]	T [m]	H [m]
1	Blue Amber	design	197.00	7.47	3.52	1.87	56.00	7.50	14.00
2	Innovation	2015	147.50	5.73	3.51	1.50	42.00	7.33	11.00
4	Pacific Orca	2012	160.90	8.91	3.28	1.89	49.00	5.50	10.40
5	Seajacks Scylla	2015	139.00	8.33	2.78	1.83	50.00	6.00	11.00
6	Ulam	design	199.09	8.27	3.21	1.71	62.00	7.50	12.80
7	Voltaire	2022	169.30	8.00	2.82	1.95	60.00	7.50	14.60
8	Vole au vent	2013	140.40	6.51	3.42	1.51	41.00	6.30	9.50

At this stage of the ship design process, empirical formulas are applied when available, and a series of assumptions are adopted. Jack-up vessels for the transportation and installation of wind turbines are not yet mass-produced, which means there are no established empirical formulas available for determining their main dimensions. For such vessels, key

dimensions such as length and breadth are primarily determined by the number and size of the turbines to be transported.

The designed vessel will be configured to transport six wind turbines. For the Polish offshore concessions, the planned installations involve wind turbines with a capacity of 14 MW. Using available sources [37], a table was created summarizing the technical parameters of 10 MW and 15 MW wind turbines, Table 2. Subsequently, the dimensions of individual turbine components were estimated and compiled in Table 3.

Table 2. Technical parameters of large wind turbines, to be erected by the installation vessel [37].

Part	Height [m]	Weight [t]	Diameter [m]	Length [m]
Technical parameters of 10 MW wind turbine				
Tower	119	605	8	-
Nacelle	-	674	-	-
Blade	-	41	-	86
Technical parameters of 15 MW wind turbine				
Tower	150	860	10	-
Nacelle	-	1017	-	-
Blade	-	65	-	117

Table 3. Estimated technical parameters of 14 MW wind turbine, to be erected by the designed installation vessel.

Technical Parameters of 14 MW Wind Turbine				
Part	Height [m]	Weight [t]	Diameter [m]	Length [m]
Tower	144	809	9.5	-
Nacelle	-	948	-	-
Blade	-	60	-	111

Additionally, based on the available data, the nacelle's width was determined to be 8 m, and its length was determined to be 20 m. After estimating the technical parameters of the wind turbine components, it was possible to position them on a conceptual deck view of the vessel. This view, shown in Figure 3, maintains the proportions of the vessel and the dimensions of the turbine components. Based on this arrangement, the length between perpendiculars (LOA) and the breadth (B) of the designed vessel were determined.

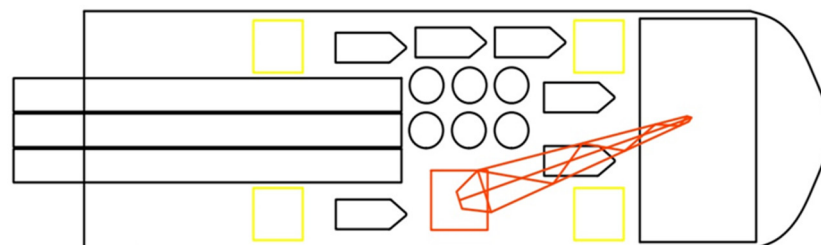


Figure 3. The arrangement of the transported stack of components for 6 turbines on the deck of the installation vessel.

2.2. Determination of Main Dimensions and Hull Weight Estimation

The selection of the ship's main dimensions and lightship weight estimation is fundamental to the long-term performance, efficiency, and environmental impact of the vessel

throughout its life cycle and impacts the consecutive design, construction, operation, and decommissioning stages. The main dimensions—length, breadth, depth, and draft—determine the hull form, payload capacity, and hydrodynamic efficiency of an offshore ship. Their selection is interdependent with operational requirements and directly influences the ship's life cycle assessment (LCA) merits.

The relationship between the length-to-breadth (L/B) ratio and resistance determines the propulsion power needed to sustain desired operational speeds. Suboptimal L/B ratios can lead to excessive fuel consumption, higher greenhouse gas (GHG) emissions, and increased operational costs. The L/B ratio influences the area of the deck, which is very important installation operations of the wind turbine installation vessel. A smaller L/B ratio improves the ship's installation operational capabilities and stability, while a larger L/B ratio favors better resistance/propulsion characteristics. This reduces fuel consumption and lowers GHG emissions, which play a significant role in LCA analysis. These two criteria are in conflict, and the design process should aim to find a reasonable optimum. Draft selection affects the wave-making resistance and maneuverability. For offshore ships operating in variable-depth environments, draft constraints necessitate careful optimization to minimize energy losses. Larger dimensions often necessitate stronger structural reinforcements, affecting material usage and weight. This has a direct impact on embodied energy and carbon during the manufacturing phase. Lightship weight estimation encompasses the structural weight, outfitting, and machinery weight, without payload and stores. Accurate prediction at the preliminary design stage is essential for achieving buoyancy—weight balance.

In general, a smaller lightship weight always improves the environmental merits in all phases of the life cycle but can adversely impact safety requirements. An underweight design may compromise strength, requiring retrofitting that increases life cycle costs and environmental footprint. Exact lightship weight estimates guide the selection of materials for the hull and superstructure and impact the manufacturing phase in terms of emissions. Ships with poorly optimized dimensions or weights often face frequent retrofitting to meet operational requirements or regulatory standards. These interventions increase costs and environmental impacts over the life span of the vessel, especially maintenance and retrofitting phases.

As the first step, the breadth B and length overall LOA were chosen on the basis of functional considerations related to the arrangement of wind turbine elements, as shown in Figure 3, to be installed on the deck of the vessel after a few iterations. Then, a statistical relation for $T = f(B)$ was prepared for the relevant ships from the database, as shown in Figure 4.

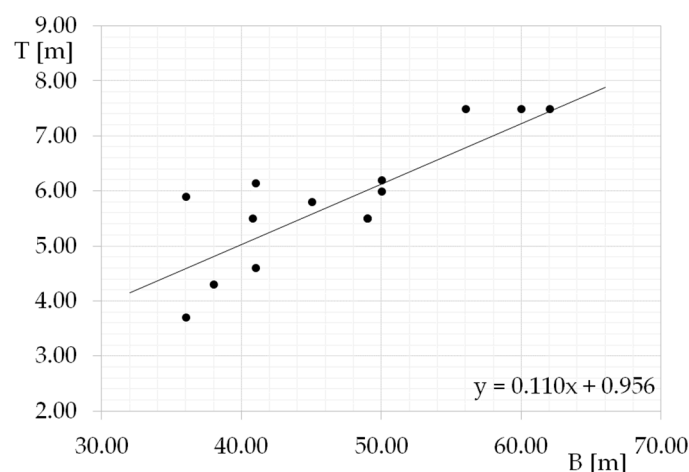


Figure 4. The relation $T = f(B)$ used to determine the draft of the vessel.

Using this formula, it was possible to determine the draft of the ship, and then, the same approach was used to determine the ship's hull height, as shown in Figure 5. At this stage, four most important hull dimensions were estimated: LOA, B, T, and H.

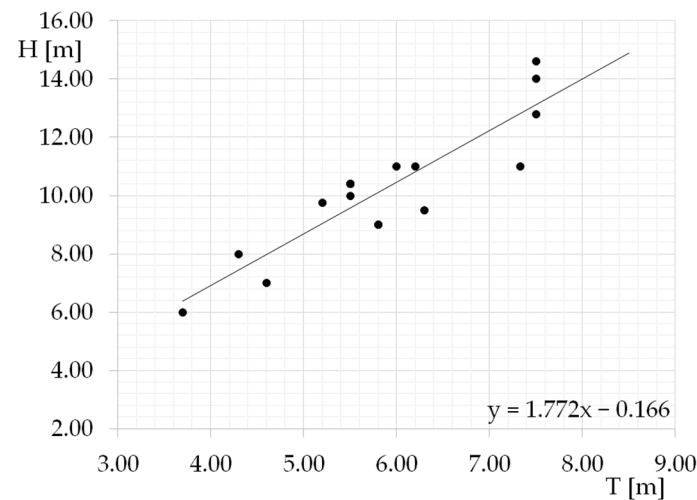


Figure 5. The relation $H = f(T)$ used to determine the height of the vessel.

The next step is to make an attempt to estimate the ship's lightship weight LSW and displacement D. These are characteristics needed to ensure the balance between gravitational and buoyancy forces providing basic floating capability.

Displacement of a ship is expressed by the following formula:

$$D = \nabla \cdot \rho \cdot k, \quad \nabla = L \cdot B \cdot T \cdot C_B \quad (1)$$

where L, B, and T are ship dimensions, and the waterline length is used here; we assume the length overall for the first estimation; ∇ is the hull volume; C_B is the ship's hull block coefficient; ρ is the water density; $\rho = 1.025 \text{ t/m}^3$; k is the appendage coefficient; $k \approx 1.005$.

For this estimation, we derived a statistical relation with the following form: $D = f(LBT)$, where displacement is expressed as the product of the main dimensions, as shown in Figure 6.

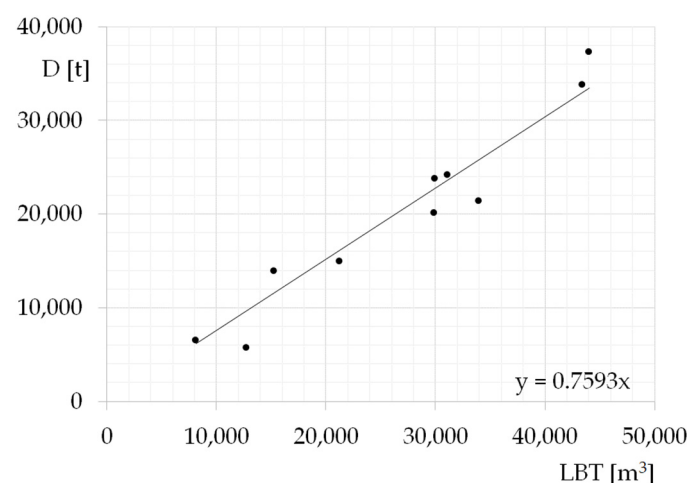


Figure 6. The relation $D = f(LBT)$ used to determine the displacement of the vessel.

The estimation of lightship weight LSW is more difficult at this stage, since there is no physical formula that can be used. LSW mostly depends upon three main dimensions: L, B, and the ship's hull height H, as they represent a steel block around a ship's structure, but

there is no linearity between these variables. It was assumed that a statistical formula of the following form would be useful for this estimation:

$$LSW = a \cdot L^{k_1} \cdot B^{k_2} \cdot H^{k_3} \quad (2)$$

To find coefficients a , k_1 , k_2 , and k_3 in this equation, the ships from the database for which lightship weight data were available were used. The data were used to perform a logarithmic transformation of both sides of the equation to linearize it.

This allowed us to use multiple linear regression techniques to estimate coefficients, using ordinary least squares regression. The results are the following: $a = 0.0238$, $k_1 = 1.121$, $k_2 = 1.991$, and $k_3 = 0.195$, and the formula explaining the lightship weight LSW of a wind turbine installation vessel as a function of L , B , and H , has the following form:

$$LSW = 0.0238 \cdot L^{1.121} \cdot B^{1.991} \cdot H^{0.195} \quad (3)$$

The model presented relatively good overall performance, with the correlation coefficient $R^2 = 0.953$ calculated for all predicated and database pairs, and the mean relative error was 14.5%, with the largest errors for smaller ships in the database.

Using the formula presented in Figure 6 and Formulas (1) and (3), it was possible to determine the block coefficient, $C_B = 0.74$. For further calculations, we adopted the value of $C_B = 0.8$ to ensure the buoyancy reserve and to correct for the difference between the length overall LOA used in the statistics above, and the ship's length of the waterline LWL. Then, Equation (1) was recalculated for the new value of D . The resultant deadweight DWT was calculated as well. Treating the vessel's deadweight tonnage (DWT) at this stage of design and for this type of vessel as a resultant parameter—derived from the specified displacement and the lightship weight characteristics—is entirely appropriate. The cargo requirements primarily pertain to ensuring adequate deck area, while the total weight of the transported cargo is of secondary importance.

The relations developed statistically (Figures 4–6 and Formula (3)) are valid within the range of the minimum and maximum geometrical and mass parameters of the similar ships contained in the database with an extrapolation margin of 5%. The parameters' applicability is presented in Table 4.

Table 4. The limitations of the ship's particulars for the use of the developed statistical relations, with an extrapolation margin of 5%.

Technical Characteristics	Symbol	Min. Value	Max. Value	Unit
Length	L	60	216.0	[m]
Breadth	B	36	62.0	[m]
Height	H	6	15.0	[m]
Draft	T	3.5	8.0	[m]
Displacement	D	5700	85,000	[t]

The summary of estimations made in this section is presented in Table 5. The main ship particulars serve as an input to the next step of the preliminary design phase, namely, the assessment of the ship's power requirements, and in the case of the wind turbine installation vessels, at least two operational modes are important. The first is the free-running transit mode, and the second is the dynamic positioning (DP) mode, in which the ship prepares itself for the working, elevated position.

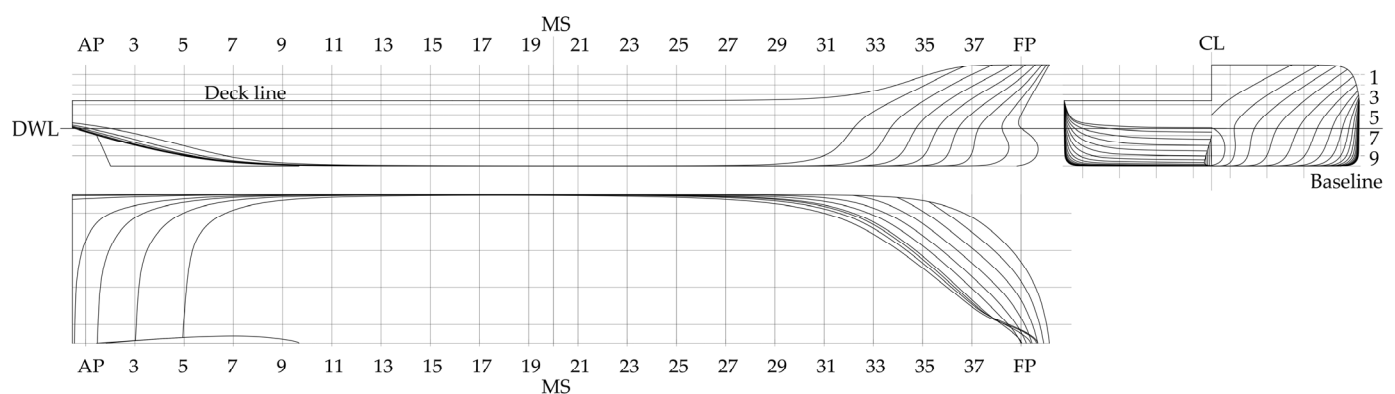
Table 5. The summary of estimations of main particulars and mass characteristics.

Technical Characteristics	Symbol	Value	Unit
Length overall	LOA	212.0	[m]
Waterline length	LWL	205.8	[m]
Breadth	B	64.0	[m]
Height	H	14.0	[m]
Draft	T	8.0	[m]
Block coefficient	C_B	0.8	[-]
Displacement	D	86,240	[t]
Lightship weight	LSW	59,104	[t]
DWT	DWT	27,136	[t]

2.3. Hull Shape Design and Hydrostatics

With the main particulars estimated in the previous section, the hull shape was designed. The hull shape directly impacts hydrodynamic resistance during transit. A streamlined design minimizes fuel consumption by reducing drag, lowering operational energy demand, and thus decreasing greenhouse gas emissions during the vessel's operational life cycle. The shape of the hull should balance transit efficiency with stability during dynamic positioning (DP) operations and when the vessel is stationary for installation tasks.

The designed hull shape is presented in Figure 7, and a 3D view of the hull is presented in Figure 8. The most important inputs for the shape design are obviously the main particulars of the vessel and the hull shape coefficients, the block coefficient in this case, as it was previously determined. The skeg was designed to improve directional stability since the transom must be very wide to ensure the required large area of the deck. For vessels with a small L/B ratio, the skeg also minimizes yawing and rolling motions, and the flat shape of the stern lines provides better versatility for DP thruster arrangement.

**Figure 7.** The lines plan of the design vessel.

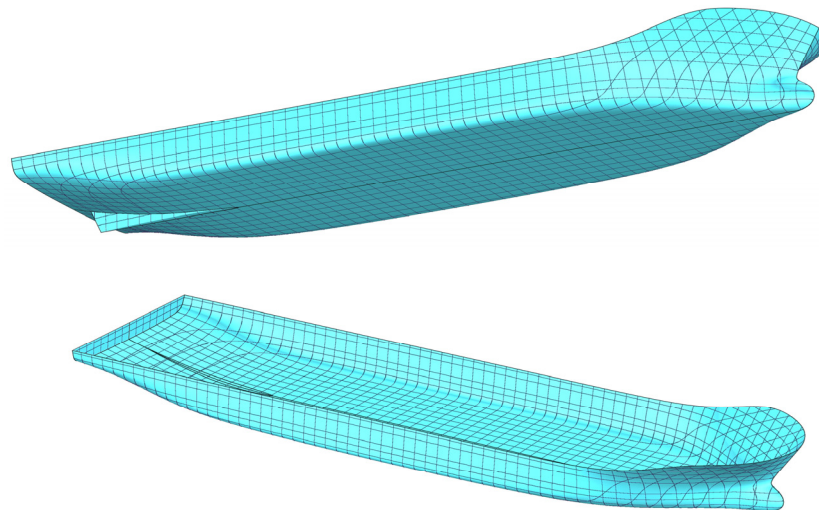


Figure 8. A 3D view of the vessel.

Hydrostatics parameters were calculated along with the hull shape design to ensure all of the necessary requirements related to buoyancy and stability. The results are presented in Table 6.

Table 6. Hydrostatics particulars of the designed hull.

Hydrostatics Particular	Value	Unit
WL Length	205.5	[m]
Breadth max on WL	64	[m]
Wetted Area	14,230.5	[m ²]
Max sectional area	507.3	[m ²]
Waterplane Area	11,625.2	[m ²]
Prismatic coefficient (C_P)	0.8	[-]
Block coefficient (C_B)	0.80	[-]
Sectional area coefficient (C_M)	0.99	[-]
Waterplane area coefficient (C_{WP})	0.88	[-]
Longitudinal position of buoyancy center KB, from aft perpendicular AP	99.7	[m]
Longitudinal position of floatation center LCF, from aft perpendicular AP	92.4	[m]
Vertical position of buoyancy center KB	4.2	[m]
Transversal metacentric radius BMt	43.5	[m]
Longitudinal metacentric radius BMI	405.1	[m]
Metacentric height above the keel, transversal KMt	47.8	[m]
Metacentric height above the keel, longitudinal KMI	409.3	[m]
hull shape slenderness ratio $\frac{L}{\sqrt[3]{V}}$	4.7	[-]

As was expected, the hull has relatively large values of hydrostatics parameters important for stability, both transverse (small) and longitudinal (large) metacentric radii are sufficient, and this should result in good initial stability and large initial values of the righting moment. The longitudinal position of buoyancy is located almost amidship, which should be neutral for resistance characteristics and ensure trimming control.

2.4. Power Estimation

The estimation of a ship's power plant is crucial for the life cycle assessment (LCA) of a wind turbine installation vessel. The power plant directly influences the vessel's environmental impact across various operational modes. The power plant is a major contributor to emissions and energy use. WTIVs operate in a range of modes, each with distinct power requirements:

- **Transit mode**—the movement of the vessel between ports or installation sites. This mode requires propulsion power; emissions are influenced by speed, hull resistance, range, and fuel type.
- **Dynamic positioning (DP) mode**—used during turbine installation to maintain position in varying environmental conditions (e.g., wind, waves, and currents). It is a high-energy-demand mode that often requires multiple thrusters and significant auxiliary power.
- **Stationary installation mode**—includes jacking up the vessel (for jack-up WTIVs), crane operations, and lifting turbine components. Power is mainly used for cranes, jacking systems, and auxiliary systems rather than propulsion.
- **Standby or idle mode**—occurs when the vessel is stationary but not actively installing turbines. This mode has a minimal power demand for basic hoteling and auxiliary systems.
- **Port operations mode, ballasting, and deballasting**—involves docking, loading turbines, and maintenance. Power is needed for maneuvering, cargo handling, and auxiliary systems. This mode is used to adjust the vessel's draft and stability and involves significant auxiliary power use for pumps.

For the analysis presented in this paper, we have selected the following profiles to be estimated for the purpose of power generation:

1. **Transit mode**, as this operation represents a significant portion of the vessel's operational profile, especially when moving between ports and installation sites. Here, the propulsion system's power requirements and fuel consumption during transit largely dictate the design of the main engines and the overall efficiency of the power plant.
2. **Dynamic positioning (DP) mode**; the reason is the DP work is a critical, high-energy-demand mode that drives the sizing of thrusters and auxiliary power systems. Thruster power requirements depend on environmental conditions (e.g., wind, waves, and currents), vessel size, and positioning precision, making this mode essential for determining the power plant's peak auxiliary load.
3. **Stationary installation mode**. Power requirements for these systems influence the sizing of auxiliary engines, especially since propulsion is minimal during this mode.

It is anticipated that the stationary installation mode, except in some extraordinary situations, e.g., concurrent operations of cranes, jacking systems, and ballast pumps causing temporary spikes in energy demand, should not exceed the power requirements of the transit or DP modes.

2.4.1. Power Estimation in Transit Mode

In the case of the transit mode, hull resistance calculations were carried out using the statistical Holtrop–Mennen method [38]. This method is an empirical, statistical approach used to estimate the total resistance of a ship's hull in calm water. It is applied in preliminary ship design and performance prediction. It is based on regression analysis of a large database of model test results from various ship hull forms and provides an estimation of the total resistance components, including frictional resistance, residual resistance (wave-

making and eddy resistance), and additional resistance components, such as appendage resistance and bulbous bow effects [38].

This scenario pertains to the vessel freely navigating at a constant speed to the location where it will perform offshore wind turbine installation operations. A design speed of 12 knots was assumed for this mode. Generally, the transit mode has lower energy demands compared to operations in the dynamic positioning (DP) mode; however, this is subject to variations depending on prevailing sea condition, wind, and wave parameters. For this case, and at a speed of 12 knots, the hull resistance was determined to be $R_T = 773$ kN.

Based on the results of resistance calculations, the maximum propulsion power demand for transit for the ship's power plant is determined using the following formula:

$$P = k \frac{R_T \cdot V}{\eta} \quad (4)$$

where P is the propulsion power [kW], R_T is the total ship resistance during transit speed, [kN], V is the vessel's speed [m/s], η is the overall propulsion efficiency, and k is the sea margin.

The overall propulsion demand in the transit mode, assuming that $k = 10\%$ and $\eta = 60\%$, will be $P = 8800$ kW. The typical values of ships' propulsion efficiencies and sea margin values can be found in [39,40].

2.4.2. Power Estimation—DP Mode

Estimation for the DP operations should include considerations for the environment, namely, waves, wind, and current forces, and it should take into account the worst adopted scenario. We applied here the method of calculation presented in [41,42] and with the relevant approach to data on necessary coefficients used for calculations. The coefficients necessary to compute environmental loads were adapted from the data for similar or functionally similar ships. The forces acting on a floating unit cause a displacement of its position from the desired, maintained position. Calculating the external forces exerted by the marine environment is essential for determining the total required thrust and power and selecting the equipment for the dynamic positioning system. The calculations of the external forces acting on the vessel due to the marine environment are based on the assumed data provided in Table 7.

Table 7. The input dataset used for external forces calculation.

Variable	Symbol	Value	Unit
Wind speed	V_A	10	[m/s]
Current speed	V_C	1	[m/s]
Wave height	H_S	4	[m]
Average wave period	T_1	5	[s]
Wind direction relative to the vessel	β_A	$0 \div 180$	[°]
Wave direction relative to the vessel	β_W	$0 \div 180$	[°]
Current direction relative to the vessel	β_C	$0 \div 180$	[°]
Coefficients increasing drag relative to environmental forces	C_{TX}, C_{TY}, C_{TM}	1,1	[-]
Regular wave frequency	ω	$0.2 \div 0.4$	[1/s]

To carry out the calculations of the subsequent stages, it was necessary to calculate the projection of the frontal windage area, the projection of the side windage area, and the projection of the underwater lateral area of the hull onto the symmetry plane. The first two values were calculated based on data from a similar vessel due to the lack of data for

the designed vessel necessary for these calculations at this stage of the project. The results are presented in Table 8.

Table 8. Summary of ship's projected areas.

Ship Particular	Symbol	Value	Unit
Projection of the frontal area	S_X	2496	[m ²]
Projection of the side area	S_Y	4500	[m ²]
Projection of the side underwater area in the symmetry plane	F	1615	[m ²]

Estimation of wind forces. The average wind forces acting on the positioned vessel at a vessel speed of $V = 0$ can be calculated using the formulas below. The calculation results are compiled in Table 9.

$$R_{AX} = \frac{1}{2} \rho_A S_X V_A^2 C_{AX}(\beta_A) \quad (5)$$

$$R_{AY} = \frac{1}{2} \rho_A S_Y V_A^2 C_{AY}(\beta_A) \quad (6)$$

$$M_{AZ} = \frac{1}{2} \rho_A S_Y L V_A^2 C_{Am}(\beta_A) \quad (7)$$

where ρ_A is the air density [kg/m³], S_X is the projection of the frontal area [m²], S_Y is the projection of the side area [m²], L is the ship length [m], V_A is the wind speed [m/s], C_{AX} , C_{AY} , and $C_{Am}(\beta_A)$ are the coefficients of aerodynamic drag, which are functions of the relative wind direction (β_A), and β_A is the relative wind direction.

Table 9. Average wind forces calculation result.

β_A [°]	R_{AX} [kN]	R_{AY} [kN]	M_{AZ} [kNm]
0	60.3	0.0	0.0
30	87.6	129.4	−5145.2
60	57.4	183.7	−4720.9
90	−14.4	214.8	−954.8
120	−34.4	219.9	2121.8
150	−80.4	103.5	3023.5
180	−63.2	0.0	0.0

Estimation of current forces. The average forces exerted by the current on a dynamically positioned vessel at a ship velocity of $V = 0$ were calculated using the following equations. The calculation results are presented in Table 10.

$$R_{CX} = \frac{1}{2} \rho_W F V_C^2 C_{CX}(\beta_C) \quad (8)$$

$$R_{CY} = \frac{1}{2} \rho_W F V_C^2 C_{CY}(\beta_C) \quad (9)$$

$$M_{CZ} = -\frac{1}{2} \rho_W F L V_C^2 C_{Cm}(\beta_C) \quad (10)$$

where ρ_W is the water density [kg/m³], F is the projection of the underwater side surface of the hull on the symmetry plane [m²], L is the ship length [m], V_C is the current velocity [m/s], C_{CX} , C_{CY} , and C_{Cm} are the coefficients of forces and moment of resistance due to the ocean current, and β_C is the current direction relative to the vessel.

Table 10. Forces exerted by the current.

$\beta_C [^\circ]$	$R_{CX} [kN]$	$R_{CY} [kN]$	$M_{Cz} [kNm]$
0	8.9	0.0	0.0
30	20.4	325.6	−11,680.3
60	18.7	651.2	−13,348.9
90	0.8	691.9	0.0
120	−16.3	651.2	10,011.7
150	−22.8	325.6	11,680.3
180	−12.2	0.0	0.0

Here, we consider the effect of wave action on a dynamically positioned vessel. The average forces exerted by an irregular wave on a dynamically positioned vessel at a ship velocity of $V = 0$ can be calculated using the formulas below:

$$R_{WX} = -2\rho_W g \frac{B^2}{L} \int_0^\infty C_{WX} \left(\frac{\omega}{\beta_W}, V \right) S_{\xi\xi}(\omega) d\omega \quad (11)$$

$$R_{WY} = -2\rho_W g \frac{B^2}{L} \int_0^\infty C_{WY} \left(\frac{\omega}{\beta_W}, V \right) S_{\xi\xi}(\omega) d\omega \quad (12)$$

$$M_{WZ} = 2\rho_W g B^2 \int_0^\infty C_{Wm} \left(\frac{\omega}{\beta_W}, V \right) S_{\xi\xi}(\omega) d\omega \quad (13)$$

where ρ_W is the water density [kg/m^3], g is the gravitational acceleration [m/s^2], B is the ship breadth [m], C_{WX} , C_{WY} , and C_{Wm} are the wave drift force coefficients for regular waves, dependent on the wave direction relative to the ship (β_W), ω is the regular wave frequency, β_W is the wave direction relative to the ship, and $S_{\xi\xi}(\omega)$ is the spectral energy density function of wave motion.

Spectral energy density of wave motion. Before calculating the effect of wave action on a dynamically positioned vessel, it was necessary to determine the standard spectral energy density of wave motion. The following formula was used for the calculations:

$$S_{\xi\xi}(\omega) = A \omega^{-5} \exp\left(-\frac{B}{\omega^4}\right) \quad (14)$$

where A and B are variables depending on the wave parameters, $A = 173 \frac{H_s^2}{T_1^4}$ and $B = \frac{691}{T_1^4}$, H_s is the significant wave height, and T_1 is the wave period.

A summary of the calculated values is presented in Table 11 (spectral energy density of waves) and Table 12 (wave drift forces).

The resultant forces of the marine environment can be calculated as follows:

$$R_{SX} = R_{AX} + R_{WX} + R_{CX} \quad (15)$$

$$R_{SY} = R_{AY} + R_{WY} + R_{CY} \quad (16)$$

$$M_{SZ} = M_{AZ} + M_{WZ} + M_{CZ} \quad (17)$$

During position keeping, the total resultant thrust of all thrusters in the DP system must exceed the total resultant environmental forces acting on the vessel, even under the worst-case scenario of the assumed environmental parameters. This is necessary to maintain system redundancy and account for momentary peaks in loads. For this reason, the calculated thrust forces of the thrusters are increased by 10%. The results of the

calculations for the resultant thrust force of the DP system's thrusters are presented in Table 13.

Table 11. Results of calculations of spectral energy density.

ω	Spectral Energy Density	Unit
0.2	0.0	[m ² s]
0.4	7.6×10^{-17}	[m ² s]
0.6	1.1×10^{-2}	[m ² s]
0.8	9.1×10^{-1}	[m ² s]
1.0	1.5	[m ² s]
1.2	1.0	[m ² s]
1.4	6.2×10^{-1}	[m ² s]

Table 12. Results of wave forces calculations.

β_C [°]	Rwx [kN]	Rwy [kN]	Mwz [kNm]
0	184.0	0.0	0.0
30	240.8	229.7	−5748.4
60	301.0	897.7	−4785.3
90	−4.3	1943.1	2005.8
120	−344.9	951.9	−8498.8
150	−223.6	231.8	2585.0
180	−180.8	0.0	890.6

Table 13. Results of thrust forces calculation.

T _{CX} [kN]	T _{CY} [kN]	M _{CZ} [kNm]
278.6	0.0	0.0
383.6	753.1	−24,831.4
414.9	1905.9	−25,140.6
−19.7	3134.8 *	1156.1
−435.2	2005.3	3998.1
−359.4	726.9	19,017.7
−281.7	0.0	979.7

* The maximum value of thrust to be delivered by ship's power system

The resultant required thrust forces of the DP system's thrusters:

$$T_{CX} = C_{TX} \cdot R_{SX} \quad (18)$$

$$T_{CY} = C_{TY} \cdot R_{SY} \quad (19)$$

$$M_{CZ} = C_{TZ} \cdot M_{SZ} \quad (20)$$

where R_{SX} , R_{SY} , and R_{SZ} are the total environmental forces acting on the vessel (worst DP scenario), T_{CX} , T_{CY} , and T_{CZ} are the total thrust forces generated by all thrusters, including the main propulsion system, and C_{TX} , C_{TY} , and C_{TZ} are the coefficients increasing the thrust relative to the environmental forces acting on the vessel.

The table above presents the results of the calculations for the total forces exerted by the marine environment in the most power-demanding scenario, where the largest wind, current, and wave forces are assumed to act simultaneously from the same direction. This represents an extreme case, the occurrence of which is expected to be rare under normal operational conditions, but it cannot be entirely ruled out. In this situation, the required (lateral) thrust should be not less than **3135 kN**, see **Table 13**.

The estimation of power for the required thrust is based on a typical coefficient of specific thrust related to the power input. The total power load needed for the DP mode can be estimated as follows:

$$P_{DP} = \frac{T_P}{C_P} \quad (21)$$

where P_{DP} is the total power of the DP thrusters, [kW], T_P is the total thrust generated by the DP thrusters, [kN], and C_P is the specific thrust-to-power coefficient for a given thruster, assumed 0.16 [kN/kW], e.g., on the basis of information in [43].

According to Formula (21), the total power needed for DP operations can reach up to 19.6 MW in the most unfavorable conditions. This is the power that should be used for the purpose of propellers/thruster configuration layout. Two aft propellers of the azimuthing pulling type that provide propulsion during free running participate in the DP operations; thus, the 8.8 MW (4.400 MW each propeller) needed for propulsion can be included. The remaining 10.8 MW should be allocated, e.g., among two bow thrusters and one stern thruster, but the subject of thrust allocation is not under consideration for the scope of this paper.

The ship's power plant working in the DP mode must ensure sufficient thrust for the DP system, with redundancy for peak loads, while also supplying energy to essential auxiliary systems like ventilation, air conditioning, lighting, navigation, communication, and refrigeration.

2.4.3. Power Estimation—Stationary Installation Mode

The stationary installation mode of a wind turbine installation vessel (WTIV) is the situation when installing operations are carried out while the vessel is raised on its legs or the legs are being deployed. The following types of energy demand are to be considered: jack-up system power, the load needed for crane operations, supporting systems such as lighting, heating, ventilation, air conditioning (HVAC), and accommodation for personnel on board, and environmental and ballast systems. The loads during the stationary installation mode were estimated on the basis of the power needed for the jacking-up system, crane, and loads necessary for powering other ship systems. The results are presented in **Table 14**.

Table 14. Power loads for stationary installation mode.

No.	System	Power Load Max. [kW]
1	Jack-up system	4000
2	Main crane	1500
4	Pumps, power plant systems	500
5	Other ship systems (HVAC, navigation, lights, etc.)	1200
	Total	6750

The results of calculations from Sections 2.4.1–2.4.3 were presented in **Table 15** in the form of a simplified power balance for the purpose of the selection of ship generators and,

what is more important for the objective of this paper, the LCA analysis. The total installed power should not be less than 21.3 MW.

Table 15. Power balance for the considered cases.

Operational Mode	Propulsion Thrusters [kW]	DP Thrusters [kW]	Jack Up [kW]	Main Crane [kW]	Pumps, Power Plant, Other Loads [kW]	Max. Total Load [kW]
Free-running transit	8800	-	-	-	1700	10,500
DP work	8800	10,800	-	-	1700	21,300
Jacking-up and installation work	-	-	4000	1500	1700	7200

2.5. General Arrangement

On the basis of the mission profile and the selected main particulars, the general arrangement of the ship was prepared. The deck size was informed by the desired turbine characteristics and the number to be installed. Accommodation was planned in the fore part of the ship, the engine room below the working deck area, as it requires a significant portion of space for the power generators and systems. The necessary tanks, ballast, fuel, etc. provide volume for stores and maintain ship stability and trim. The hull is divided into watertight compartments providing boundaries between functional areas. The space for lowering the jacking-up system consists of four moonpools. Frame spacing of 0.7 m was adopted. The result spatial planning of the vessel is presented in Figure 9.

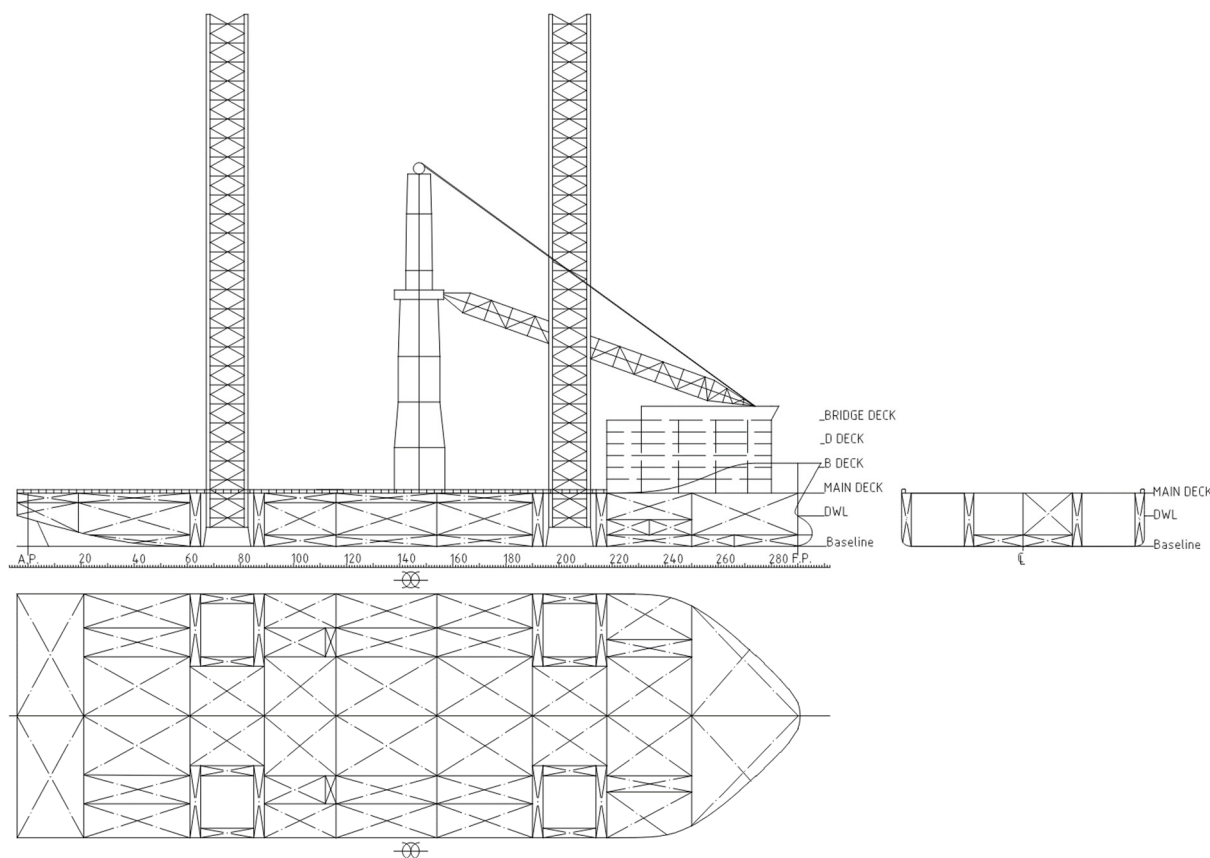


Figure 9. General arrangement of the designed vessel.

2.6. Life Cycle Analysis of the Design

In Sections 2.1–2.5, the very initial phases of ship design for the case of a wind turbine installation vessel were presented to make a first estimation of basic ship technical parameters. In usual design practice, at this stage, the LCA analysis is not performed, especially for an offshore vessel, since there are not sufficient details on a design related to all installed systems and other technical specifications. Our intention is to introduce this possibility and to show that it is still feasible and purposeful to propose the application of the LCA for such early design stages and to make an attempt at the parametrization of the LCA merits as a function of the ship's main particulars.

Let the boundaries of the LCA, for the presented analysis, be the following phases of the life cycle:

- Shipbuilding;
- Operation;
- Maintenance;
- Dismantling.

Shipbuilding, dismantling, and maintenance are the phases where shipyard-like processes dominate, with the use of energy and materials and cutting, welding, transport, sandblasting, and painting processes dominating. It is clear that these phases are mostly dependent on two factors: material amount (structure mass or surface to be processed) and the local energy use and supply. Whereas the latter factor is out of the scope of the analysis of this paper and can be incorporated by the particular design, the former can be taken into account.

Shipbuilding and dismantling emissions are related to the mass parameter. The transport and spatial structure's completion or dismantling processes dominate these phases. The total emissions are mostly related to the mass of the structure to be erected, and for ships, they depend on the lightship weight. The lightship weight has been defined by Formulas (2) and (3), and it is the function of the main ship dimensions.

Maintenance emission sources are the processes related to the periodical drydocking of a ship. The most important processes that contribute in this case are cleaning, sandblasting, painting, occasional cutting, and welding. Maintenance emission sources are the function of the ship surface processes, and the relevant ship geometrical design variable for parametrization is the wetted surface area (WSA) of the hull, since the processes considered here are performed mostly within the external surface of the hull. The wetted surface can be either calculated as part of hydrostatics calculations (Table 6) or, for the purpose of parametrization, regression formulas can be used, e.g., the well-known Denny–Mumford empirical formula of the following form:

$$WSA = 1.7 \cdot L \cdot T + \frac{\nabla}{T} \quad (22)$$

The considered emission, in the respective time period, can be calculated for the shipbuilding, maintenance, and dismantling phases according to the following equation:

$$E_{S,M,D,i} = k_i \cdot \alpha_i \quad (23)$$

where $E_{S,M,D,i}$ is the emission of the considered i -type [t], S , M , and D are the indexes representing the shipbuilding, maintenance, or dismantling phases, k_i is the specific emission index expressed in tons of emissions per ton of the processed steel or per area of the processed hull surface or, as we will show further, per kW of the power used, and α_i is the ship's geometrical or weight design variable used for parametrization. The emission

index k can be taken either from the existing data of other completed ships in operation or estimated on the basis of the shipyard data.

The emissions for the operational phase require more consideration. As was presented in the literature review, the operational phase contributes most to the life cycle of the vessel, and the use of the power installed in the power plant is the most significant factor. For this purpose, the time analysis (percentage of time used) of operational profiles presented in Table 15 should be carried out, and furthermore, the level of the maximum power, as defined in Table 15, utilized should be considered. Table 15 presents the maximum power installed to handle the possible peaks in loading due to the least favorable environmental forces for the DP system, and it is very unlikely that the ship would use it for a major portion of the time. This is the most important difference when analyzing emissions for offshore vessels in comparison with regular transport ships—the real emissions are dependent on environmental variables and can be the subject of probabilistic approach calculations, especially for DP operations. The following formula has been adopted to estimate the emissions for the operational phase, including three considered cases in Table 15:

$$E_{O_i} = t_{FR} \cdot k_i \cdot P_{FR} + t_{DP} \cdot k_i \cdot k_{EL} \cdot P_{DP} + t_{IW} \cdot k_i \cdot P_{IW} \quad (24)$$

where E_{O_i} is the total emission of a considered type, t_{FR} is the time percentage of the free-running operational phase, P_{FR} is the power used for free running, t_{DP} is the time percentage of the dynamic positioning operational phase, P_{DP} is the power used for the dynamic positioning operational phase, k_{EL} is the maximum power loading factor from environmental forces, t_{IW} is the time percentage of installation work in the operational phase, P_{IW} is the power used for the installation force, k_i is the specific emission index expressed in tons of emissions per kW of generated power.

For the purpose of the calculations presented in the next parts of this paper, the specific indexes of particular emissions, k_i , discussed in Formulas (23) and (24) for the considered operational phases, are defined by the means of the following parametrization:

For shipbuilding and dismantling,

$$k_i = \frac{E_{iS,D}^0}{LSW^0} \left[\frac{\text{tons of emission}}{\text{tons of steel}} \right] \quad (25)$$

For maintenance,

$$k_i = \frac{E_{iM}^0}{WSA^0} \left[\frac{\text{tons of emission}}{\text{m}^2 \text{ processed area}} \right] \quad (26)$$

For the operational phase,

$$k_i = \frac{E_{iO}^0}{P^0} \left[\frac{\text{tons of emission}}{\text{kW of installed power}} \right] \quad (27)$$

In the above formulas, index 0 denotes the emissions of the ships of reference for which the emissions can be known, and their respective design variables or characteristics (LSA, WSA, and P).

3. Results

The parametric calculation model described in the previous section was utilized to evaluate the life cycle assessment (LCA) performance of the designed wind turbine installation vessel. The emissions covered by the calculations were CO₂, CO, SO₂, NO_x, PM (all), CH₄, and VOCs, except for operational data for volatile organic compounds, where source data were missing. The purpose of the assessment was to provide an understanding of its environmental impact from the chosen emissions analyzed. Data on the specific

emission factors k_i have been estimated on the basis of data presented in [2] where the total emissions of a vessel of similar displacement were published. The source data of the vessel that was the subject of analysis for one year of operation are presented in Table 16.

Table 16. The source data emissions for the reference vessel [2], recalculated for 1 year of operation.

Emissions 1 Year		Operation	Shipbuilding	Maintenance	Dismantling	Total Life Cycle
CO ₂	tons	42,400.00	916.00	384.80	340.40	44,041
CO	tons	126.80	18.12	3.26	30.88	179
CH ₄	tons	1.12	0.16	0.06	0.09	1
NO _x	tons	1216.00	5.12	3.68	4.28	1229
PM (all)	tons	98.00	0.92	0.35	0.90	100
SO ₂	tons	628.00	4.08	2.96	5.12	640
VOC	tons		0.80	2.31	0.01	3

The shipbuilding, maintenance, and dismantling emissions are assumed to be distributed evenly within the entire life cycle, despite occurring as one-time events (shipbuilding and dismantling) or periodically (maintenance). However, this approach is justified, particularly when the presented parametric model is applied to the optimization process of the vessel's main characteristics. In such cases, the emission functions become objective functions that balance economically favorable solutions, such as the net present value. Furthermore, the reference vessel's principal characteristics were estimated (LSW and WSA), and the above emissions were parametrized to obtain the specific emission factors k_i . The result of this parametrization is presented in Table 17.

Table 17. The specific emission indexes k_i .

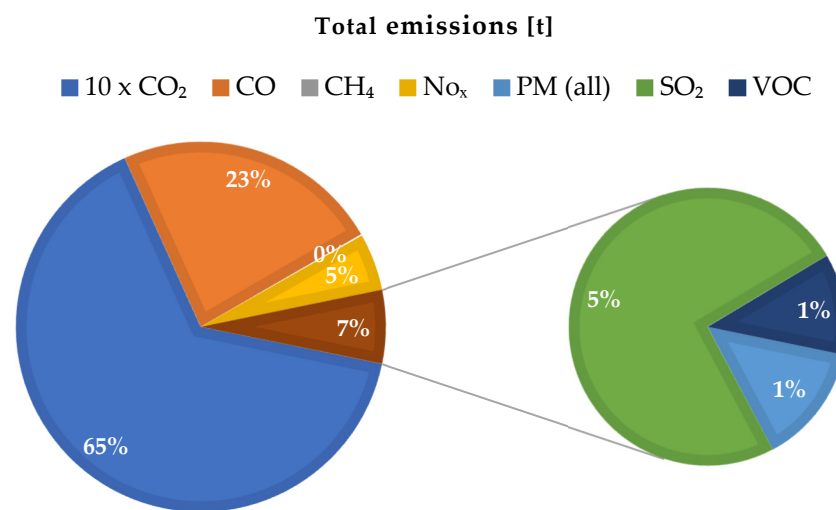
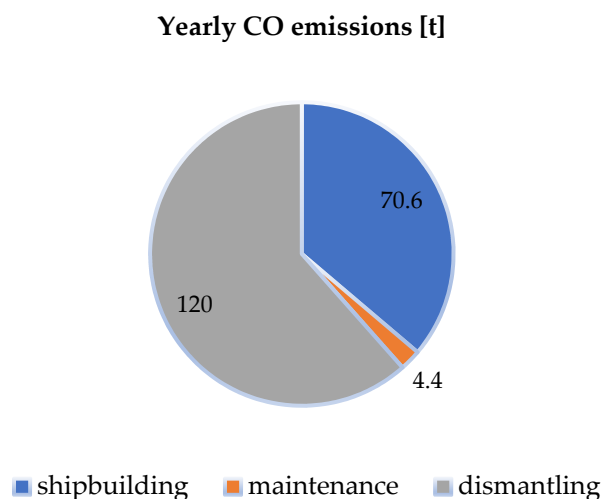
	Operation	Shipbuilding	Maintenance	Dismantling
Emission	[te*/kW]	[te*/t]	[te*/m ²]	[te*/t]
CO ₂	4.46	6.04×10^{-2}	3.66×10^{-2}	2.24×10^{-2}
CO	1.33×10^{-2}	1.19×10^{-3}	3.11×10^{-4}	2.04×10^{-3}
CH ₄	1.18×10^{-4}	1.07×10^{-5}	5.63×10^{-6}	5.62×10^{-6}
NO _x	1.28×10^{-1}	3.38×10^{-4}	3.50×10^{-4}	2.82×10^{-4}
PM (all)	1.03×10^{-2}	6.04×10^{-5}	3.31×10^{-5}	5.93×10^{-5}
SO ₂	6.61×10^{-2}	2.69×10^{-4}	2.81×10^{-4}	3.38×10^{-4}
VOC		5.27×10^{-5}	2.20×10^{-4}	7.89×10^{-7}

te*—tons of emission.

The results of the calculation of emissions per year for the shipbuilding, maintenance, and dismantling phases are presented in Table 18. The contribution of the different types of emissions under consideration is presented in Figure 10. The CO emission for different phases under consideration is presented in Figure 11.

Table 18. The results of calculation of emissions for shipbuilding, maintenance, and dismantling phases.

	Shipbuilding	Maintenance	Dismantling	Total Emissions
Emissions Yearly	[t]	[t]	[t]	[t]
CO ₂	3569.31	521.03	1326.41	5416.75
CO	70.61	4.42	120.33	195.35
CH ₄	0.63	0.08	0.33	1.04
NO _x	19.95	4.98	16.68	41.61
PM (all)	3.57	0.47	3.51	7.55
SO ₂	15.90	4.00	19.95	39.85
VOC	3.12	3.13	0.05	6.29

**Figure 10.** Contribution of different types of emissions of the wind turbine installation vessel in the total yearly emissions in the shipbuilding, maintenance, and dismantling phases.**Figure 11.** CO emissions for different phases.

The operational phase requires some assumptions to be made related to the percentage of time used for different profiles described in Table 15. Considering that the average installation time per turbine, according to the industry average [44], is approximately 2 days (min. 0.7 days per turbine, maximum 3.2), the average distance between turbines is

1 nautical mile (Nm), approx. 10xD, the vessel carries components for installing six turbines, and the distance from the installation port (e.g., port of Ustka) to the offshore wind farm can be 60 Nm, with an average port stay of 3 days per cycle, it can be assumed that the vessel will complete 15.5 installation cycles per year. This estimation also accounts for an 85% vessel utilization rate over the annual operational period. For the basic variant of calculations, it was assumed that in one operational cycle, the ship spends 1 day in the free-running transit mode, 12 days in installation work, and 4 days in the DP operations mode. The ship would spend approx. 264 days of work at sea, excluding port days.

The above assumptions lead to the following time percentage utilization of modes in Table 15 and in Formula (24): $t_{FR} = 6\%$, $t_{IW} = 71\%$, and $t_{DP} = 23\%$. For the initial calculations and illustration purposes, the maximum power loading factor k_{el} was assumed to have a value of 0.6. The results of calculations are presented in Table 19.

Table 19. Operational phase emissions calculated for the wind turbine installation vessel—different operational profiles and total emission, yearly.

	$t_{FR} = 6\%$,	$t_{DP} = 23\%$, $k_{el} = 0.6$	$t_{IW} = 71\%$	100% of op. Time
Types of Emission	Free Running—Transit	DP Operation	Installation Work	Total Emissions
	[t]	[t]	[t]	[t]
CO ₂	2811.79	10,932.51	22,815.66	36,560
CO	8.41	32.69	68.23	109
CH ₄	0.07	0.29	0.60	1
NO _x	80.64	313.54	654.34	1049
PM (all)	6.50	25.27	52.73	85
SO ₂	41.65	161.92	337.93	542

The presented calculations and inventory of emissions of the operational phase show that, in terms of the total mass of emission, the effect of greenhouse and climate influences dominate the overall impact; however, other emissions contribute substantially, with NO_x being the next largest contributor. The comparison of other emissions excluding CO₂ is presented in Figure 12.

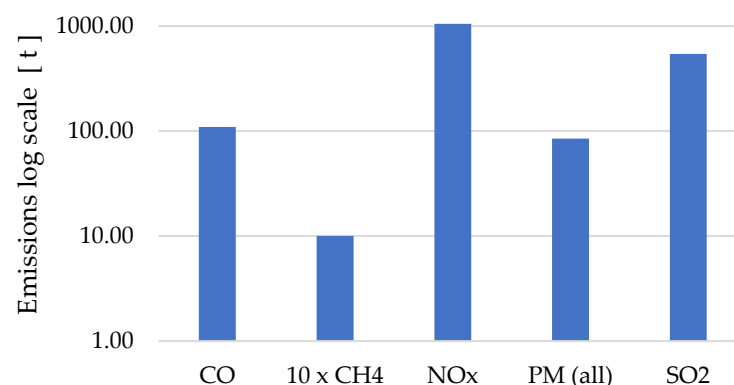


Figure 12. The comparison of emissions excluding CO₂.

4. Discussion

A key finding of this work is the significant role played by operational emissions, particularly from installation work and dynamic positioning (DP) operational modes. Unlike conventional cargo vessels, offshore installation vessels exhibit highly variable

energy demands due to their specialized functions, including DP-intensive operations and high-load crane and jacking-up system usage, as is presented in Table 15 and, for emission characteristics, in Table 19. Emissions in these types of operations highly depend on environmental loads, which are the subject of probability assessments, and in real-life operational conditions, a specific area purposed for ship design can be tailored for a particular area of planned installation activities. There is a clear need to redefine traditional EEDI-like indicators to better address the specific type of work of an offshore vessel. The uncertainty in environmental conditions affecting DP operations introduces variability in emissions calculations. Future work could explore the incorporation of probabilistic methods to refine LCA estimations under different operational scenarios in the early design stages.

The uncertainties of the presented methodology are related to the very limited availability of LCA performance databases specific to offshore vessels, and this causes a simplified approach of using parametrized factors (Table 17), which still can be relevant for the early design phases. Another source of uncertainty is related to the assumptions made for the operational phases and the respective times of these phases. In this case, a better analysis of the real-life scenarios from the operations history should improve the final emissions assessment. A cautious, iterative approach including a sensitivity analysis and data refinement is essential to enhance the proposed methodology.

We assumed here that the solution for power generation is a traditional, internal combustion type, and the influence of emerging energy-efficient technologies, such as hybrid propulsion systems and alternative fuels, could be examined within the LCA framework to determine their viability for offshore vessels. However, the rationale behind the presented research was to incorporate LCA methodology into the initial design stages regardless of the types of energy generation. If such emerging types of energy generation technologies (e.g., methanol, hydrogen, and electric propulsion) are to be included in the proposed design, the specific emission indexes k_i , calculated and presented in Table 17, should be reviewed, but the other parts of the proposed approach remain the same.

Furthermore, while operational emissions dominate the vessel's environmental impact, the shipbuilding, maintenance, and dismantling phases (Table 18 and Figure 10) also contribute significantly, particularly through steel production and structural assembly. The parametric approach used in this study demonstrates that early-stage weight estimation and a wetted surface are determinants of life cycle emissions.

To achieve a final ship design or construct a vessel with technical characteristics that are supposed to mitigate environmental risks and reduce overall emissions, it is essential to evaluate the potential environmental impact during the initial stages of the project. In the conceptual design phase, the primary objective is to ascertain the principal dimensions, their ratios, and coefficients that define the ship's shape and layout as early as possible, to take into account environmental factors. The presented integration of LCA-based analysis into the ship design spiral presents an opportunity to transition toward more sustainable vessel configurations. A multi-objective optimization framework that balances environmental, economic, and operational performance could be proposed and provide valuable insights for designers and policymakers.

Future studies should expand this approach by evaluating design alternatives to further reduce the environmental footprint of offshore vessels. Using the approach proposed in this paper, the following multicriteria optimization task can be proposed:

$$\min F(\mathbf{x}) = [\text{Env}_1(\mathbf{x}), \text{Econ}_2(\mathbf{x}), \text{Perf}_3(\mathbf{x}), \text{Saf}_4(\mathbf{x}) \dots, f_k(\mathbf{x})], \quad (28)$$

where Env, Econ, Perf, and Saf denote objective functions referring to the groups of environmental, economic, performance, and safety merits of a design, parametrized

with $\mathbf{x} = [x_1, x_1, \dots, x_n]^T$ —a vector of a design solution, being the subject of equality and inequality constraints, related to the usual constraints like buoyancy, functionality, regulatory, etc.:

$$h_i(\mathbf{x}) = 0, i = 1, \dots, I \quad g_j(\mathbf{x}) \geq 0, j = 1, \dots, J \quad (29)$$

5. Conclusions

The results of this study underline the relevance of incorporating LCA at the preliminary stages of offshore vessel design. At this stage of development, the method provides a parametric tool that can be used during initial design phases to consider different design variants from the point of view of the LCA merits and in informing early-stage design decisions for offshore wind farm installation vessels. While prior research on LCA in the maritime industry has largely focused on operational efficiency and regulatory compliance of existing ships, this study highlights the potential for integrating sustainability as a design driver rather than a post-design assessment tool.

Such an approach could improve the environmental participation of industry stakeholders, including shipowners, operators, designers, classification societies, and regulators, and the pre-investment phases where parametric studies of offshore ships are a subject of consideration. The methodology can help to attain sustainability goals and compliance with environmental, social, and governance reporting. For example, shipowners could probably have better access to financing and incentives linked to sustainability metrics. Designers may be better informed on the early design solutions. Since the boundaries of the proposed methodology include the manufacturing and dismantling phases, the methodology can be relevant for shipyards and scrapping companies.

Finally, while this study focuses on wind farm installation vessels, the proposed methodology can be extended to other offshore vessel types, such as service operation vessels (SOVs), diving support vessels, research ships, or cable-laying ships, broadening its applicability within the maritime sector in terms of a specialized vessel approach. The results could also emphasize the need for regulatory bodies and ship designers to consider LCA-driven design practices, ensuring that offshore vessels contribute positively to the sustainability goals of the maritime and renewable energy sectors.

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