Prinses Elisabeth-zone (PEZ)
Offshore windpark

Life Cycle Analysis (LCA)

(uitgevoerd door Arcadis, in opdracht van FOD Economie)

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Abbreviations

EIR: Environmental Impacts Report (Milieueffecten rapport)

EoL: End of Life

EU: European Union

GBF: Gravity-based Foundations

JF: Jacket Foundations

LCA: Life Cycle Assessment

LCOE: Levelised Cost of Energy

MFO: Marine Fuel Oil

MOG2: Modular Offshore Grid 2

MP: Monopile (Foundation)

PE (I, II, III): Prinses Elisabeth (I, II, III) referring to the three lots of the PE zone.

PEF: Product Environmental Footprint

PEZ: Princes Elisabeth Zone

XLPE: Cross-linked Poly Ethylene (cables)

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1 Introduction

1.1 The context

Offshore wind turbines are a vital part of the world's renewable energy infrastructure, providing a clean and sustainable source of electricity. However, like any form of energy production, offshore wind turbines have environmental impacts that need to be carefully considered and managed.

For the construction and exploitation of an offshore wind farm including the inter-array cables, an environmental impact assessment needs to be carried out under Belgian law as part of the environmental permit procedure. Arcadis has carried out this study for the Prinses Elisabeth-zone (PEZ) as defined in the Marine Spatial Plan 2020-2026. The assignment was given in 2022, and the study was carried out in 2023.

The description of the impact of the three wind farms in the PEZ (wind turbines and inter array-cabling) on climate and atmosphere is an important element of the impact assessment. To this aim a 'Life Cycle Analysis' (from now on referred to as LCA) was requested to estimate the energy required for the construction (including production and transport), maintenance and dismantling of PEZ wind farms and the CO_2 emissions associated with them. In section 5.2.3.1 of the EIR (Environmental Impact Report), the CO_2 emissions from producing energy with this wind park will be weighed against the CO_2 emissions released using the traditional energy mix (nuclear energy, thermal power plants, etc.).

1.2 The purpose of the study

The purpose of this study is to provide authorities with an estimate of the energy consumption and the carbon footprint of the PEZ, located at ca. 35-55 km from the coast (depending on the location of the 3 lots).

It should be noted that the terminology 'Life Cycle Analysis' (LCA) is used in this report, but there are some limitations. Indeed, a full LCA, as per ISO 14040/14044 or PEF methodology is not feasible, for the following reasons: the scope was restricted to climate change and energy use impacts, data inventory was based to previous reports of the same kind, with limited design and operational information available at this stage. Instead, the methodology applied follows a "bill of materials" approach, whereby the main material and energy flows for each activity throughout the life cycle of the wind farm were identified, quantified, and the impact calculated on the basis of a characterisation factor.

Three alternative foundation types were considered in this LCA: the monopile (MP), the jacket foundation (JF) and the gravity-based foundation (GBF). The LCA also considered the 66 kV interarray-cabling of the PEZ wind farm. This should allow to take decision when managing the environmental risks associated to this project.

For PEZ's environmental impact report (EIR) a bandwidth approach is used, considering an individual power range from 12 MW to 22 MW per turbine, as a basis for the scenarios (alternatives). The life cycle analysis (LCA) is drawn up for a 15 MW wind turbine. As of today, relevant technical information is available for 15 MW turbines, though still limited. 22 MW turbines are not (yet) available in the market; hence no technical or operational data could be found. The methodology is thus to make the calculations for a 15 MW wind turbine, and then the final impacts (carbon footprint and energy use) are scaled up to estimate impacts of a 22 MW wind turbine, using conversion factors. Given that 15 MW turbines are being produced and installed only very recently, we lack extensive data on their construction, operation and maintenance, and decommissioning. The further down the life cycle of a 15 MW turbine, the higher the uncertainties. This is true for the maintenance and even more the decommissioning steps, for which literature studies and forecasts are used to model the environmental impacts in this exercise, instead of operational data.

1.3 Wind farm object of the study

The wind turbine model considers a lifespan of 20 years, three possible foundation types (monopile, jacket, and gravity-based foundation).

Often, cables have a longer life than the turbines, and when turbines need to be replaced, cables are kept underground and used again. In this study, the lifetime considered for the cables is 20 years, to be in accordance with the lifetime of the wind turbine, as the project specifications require a full decommissioning of the infrastructure.

The carbon emissions and energy use impact assessment account for the whole life cycle stages of the offshore wind farm in the Prinses Elisabeth-zone (PEZ). In this report, the following 5 phases in the life cycle of a wind turbine are discussed for a 15/22 MW wind turbine and 66 kV inter-array cabling: the production phase, the transport phase, the construction phase, the operational (including maintenance) phase and the decommissioning phase (Figure 1. Life cycle stages for a wind farm.).

For the **production** phase, the main materials of the components of the park are considered, and the carbon footprint and energy consumption have been calculated evaluating the impacts of producing these materials.

The **transport** phase includes transport from the manufacturing location to a Belgian port (Oostende), and from there to the project area, off the coasts of Belgium. For this LCA study only manufacturing locations in Europe have been considered (assumption).

The **construction** phase regards all activities necessary to set up the wind turbines and the laying of the interarray cables to connect the turbines with the MOG2 island. MOG2 is the Modular Offshore Grid 2 managed by ELIA as part of the infrastructure for offshore wind energy generation.

The **operational** (including maintenance) phase includes the activities linked with inspection and reparation of the turbines and cables.

The **decommissioning** phase includes the activities required to remove the infrastructure from the project area, and re-use/recycling of the materials when possible. For the PEZ a complete decommissioning to the original state is assumed (including turbines, cables, erosion protection, foundations).

Waste streams generated during the different stages are not accounted for in the current assessment, as they are accounted for and modelled in the Waste Management Plan of the broader EIR study, of which this is a part.

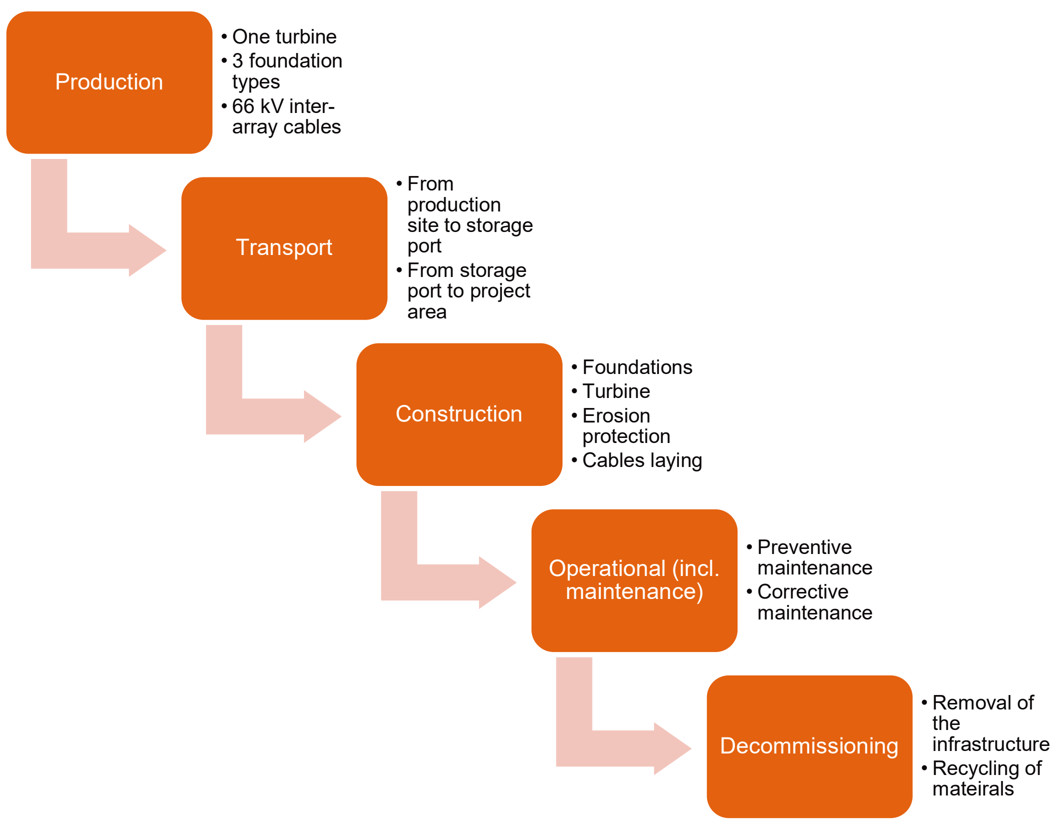

Figure 1. Life cycle stages for a wind farm.

1.4 Structure of the report

The report is structured as follows:

- Section 2 describes the LCA of a single wind turbine, including the three different foundation types (Jacket Foundation, Monopile foundation, Gravity-Based foundation). In this section, the energy consumption and carbon emissions of a 15 MW turbine are calculated, further scaled up to a 22 MW wind turbine.
- Section 3 is the LCA of the inter-array cabling (66 kV) used to connect the turbines to the MOG2 island.
- Finally, section 4 gives the total energy consumption and carbon emissions of the three lots of the PEZ and its cabling for the different foundation scenarios as outlined in the EIR.
- Relevant Annexes to support the study are attached at the end of the report.

2 Wind turbine and foundations in the PEZ

Wind turbines are a crucial technology in the transition to renewables. Over the past years, big developments have been made in technology and capacity of the wind turbines. This allowed to reach the current milestone of 15 MW wind turbines, with ongoing projects for developing 17.5 MW, 20 MW, and even 22 MW wind turbines in the upcoming years. Currently, no technical detailed 22 MW wind turbine specification sheet is available, solid enough to perform an LCA from the production stage to the end-of-life (EoL). Thus, this study is based on the publicly available technical data found for a 15 MW wind turbine, which are now starting to be installed in offshore wind projects.

At the same time, improvements in foundation technology lead to more efficient foundations, with less materials used per MWh generated by the turbine they support. The most common foundation types are the monopile foundations, the jacket foundations, and the gravity-based foundations. The choice of type of foundation derives from many factors, such as seabed type, sea depth, sea and wind characteristics, size of the turbine, characteristics of the waters, among others (Sanchez, 2019). For example, monopile foundations are usually found in more shallow waters, gravity-based foundations are used for depths up to 30 meters, above which jacket foundations are preferred (IBERDROLA, 2023).

In this study, production (manufacturing and assembly) of the wind turbines components is assumed to occur in Europe (cf. competitive tender process (offshore tender)). The foundations are usually made as close as possible to the project area. Based on previous experience, it is assumed for this study that monopile foundations and jacket foundations are manufactured in Hoboken, Belgium. For gravity-based foundations, the assumption is that they are built directly in the port (Oostende), on the same barge that will be used to transport them to the project area and that installs them on the seabed. This is due to the large dimensions and nature of this type of foundations.

Given the uncertainties in the data used for modelling the turbine and the foundations, **this study is to be considered a high-level carbon emission and energy consumption impact assessment.** It is intended to guide the reader in understanding the main hotspots in the lifecycle of the wind farm considered, as well as having an overall picture of the impacts.

2.1 Life Cycle assessment of the 15 MW offshore wind turbine

The EIR considers a bandwidth of power range between 12 MW to 22 MW. The following assessment of the impacts of one wind turbine will be based on data from the largest offshore wind turbines on the market for which limited operational data is available, i.e., 15 MW turbines. The following scaling-up step from a 15 MW model to a 22 MW model is thus based on extrapolations that will impact the results' quality and reliability (see Section 4.2).

In this impact assessment study, the wind turbine will be coupled with the three main foundations introduced above.

15 MW wind turbine

Data for a 15 MW wind turbine was taken from a technical report on 15 MW turbines by NREL (NREL, 2020), describing the main parameters of one turbine (e.g., height, rotor diameter, etc.), including the materials of the main components and their weight. The main components are assumed to be made with only one type of material. This assumption is based on the fact that the material is either the predominant one in the component, making up most of the weight, or is the one associated with the highest impact. For example, the tower is modelled as entirely made of steel. A schematic figure of a 15 MW wind turbine is presented in Figure 2.

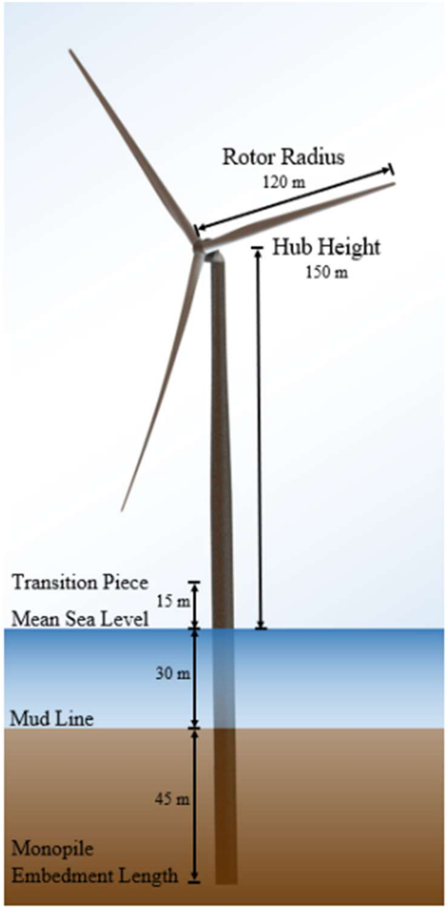

Figure 2. Scheme of the 15 MW wind turbine in the NREL report. Source: NREL

Foundations

Each park has different characteristics and foundation needs (e.g., depth of sea, salinity, strength of sea currents, type of seabed, etc.), therefore the final design of a jacket foundation will differ from one wind farm (area) to another. This level of design details cannot be accounted for in this study.

Currently, there is little data availability on the types of foundations specifically built for larger turbines (15 MW or 22 MW), as most of the wind farm installed to date use turbines up to 10 MW.

Most of the foundation data (JF, GBF) are therefore collected for smaller sized turbines and adapted to fit a 15 MW turbine. The following paragraphs detail how the data has been adapted to fit a 15 MW turbine when necessary. It should be clear to the reader that in the up-scaling step to a 22 MW turbine, the level of uncertainty on foundations will be further propagated. Figure 3 shows the three different foundation types considered in this study.

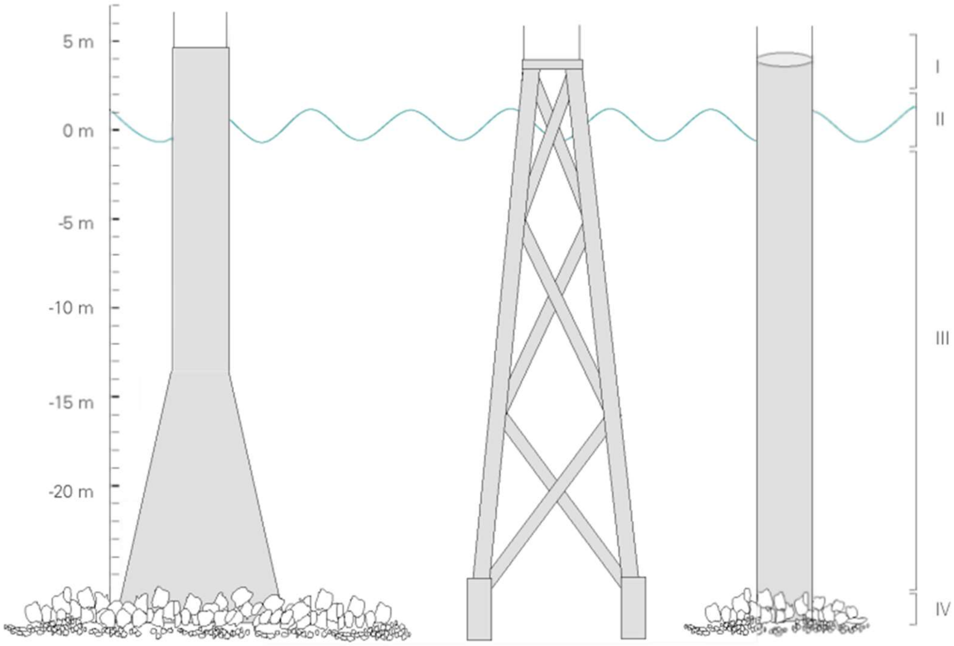

Figure 3. Three types of foundation considered in this study: (a) monopile, (b) jacket, (c) gravity based. Source: Rumes et al., 2013.

Monopile Foundations

Specific monopile foundations data was available for 15 MW turbine. This came directly from the same source as for the 15 MW turbine, i.e., NREL technical report on a 15 MW wind turbine (NREL, 2020). The monopile is a type of foundation that is driven into the seabed and upon which the turbine is attached. The main material of this foundation is steel. The weight of a monopile given in the NREL report is 1318 tons.

Jacket Foundations

Jacket foundations calculations were based on data from other current offshore wind projects and extrapolated to a 15 MW wind turbine.

While the MOG2 study used different values for a jacket foundation (IMDC, 2022), the review of those data led to the conclusion that those jacket foundations were different in terms of size and structure from the ones used for wind turbine as per our literature review. Therefore, the estimation of the weight, using data from other offshore wind turbines, despite often of smaller size, was found more relevant.

The jacket foundation is considered to be made entirely of steel, and each foundation has four anchoring steel pillars that are driven into the seabed to hold the structure in place. The amount of material (steel) used in the jacket foundation has been estimated on the basis of previous studies and technical information of installed turbines. The weight of the jacket foundation considered in this study is (an average of) 1000 tons, plus four 150-tons anchoring poles, or 600 tons for 4 poles, totalling 1600 tons of steel for the jacket foundation.

The exact weight of the foundation will likely differ, however, without more accurate data, the above is the best estimation possible based on data available in public sources (NREL, 2016), (Durakovic, 2022), (IBERDROLA, 2023).

Gravity-based Foundations

The gravity-based foundation was calculated based on the data available from the Mermaid and Northwester 2 projects, and considering data from Gravitas and C-Power GBF. This foundation is made of concrete and reinforced steel. The shape of this foundation is a truncated cone with a cylinder on top (Figure 2). The foundation is hollow inside and will be filled with filling material for its anchoring (e.g., sand). The walls of the GBF are made of a 1 m thick layer of reinforced concrete. The total height of the gravity-based foundation is assumed to be 40 meters, plus one meter for the bottom base. The truncated cone is assumed to be 20 meters tall, and the cylinder 20 meters tall. The bottom diameter of the cone is assumed to be 42 meters, with the base being 45 meters. The outer diameter of the cylinder is considered to be 22 meters. Such dimensions are derived from extrapolating data from several sources (IMDC , 2014), (ARUP, 2023), (C-POWER, 2023), (GRAVITAS, 2023) and presented in Annex 1.

The total volume of the foundation can be calculated in terms of concrete needed and steel needed starting from those values. The steel rod used to reinforce the concrete is considered to have a thickness of 0.025 meters. Considering a density of steel of 7800 kg/m3, and a density of concrete of 2500 kg/m3, the total mass of concrete used is ca. 14,000 tons, and 1,100 tons of steel. A comparison with the caissons used in the MOG2 project was made, and it was concluded that as those are tailored made for an energy island, a better estimation would be made using GBF data specific for wind turbines (IMDC, 2022).

2.1.1 Production phase

The production phase includes the manufacturing and assembly of the main parts: the turbine (including the transition piece) and the three types of foundations. The turbine is modelled with three main components: the tower, the nacelle (including the rotor hub), and the blades.

The **tower** is assumed to be made entirely of steel. This assumption is based on the fact that steel makes the largest share of tower's bill of materials and of the climate and energy impacts (Radmore, 2022).

The **nacelle** (including the rotor hub) model is simplified to overcome the intensive data gathering that would be necessary to address the complexity of this part. Indeed, the nacelle contains electro-mechanical elements which are made out of a large variety of (critical) raw materials, that can have a different environmental profile than steel. However, the latest represent a very tiny fraction of the total materials mass, compared to the mass of steel, iron, copper and aluminium. Considering the largest share of the bill of materials by weight, the nacelle is modelled as entirely made of steel (Radmore, 2022). Note: no sensitivity analysis is performed on the impact of such simplification on the results of the study.

As for the **blades**, these are typically made of carbon fibre, as they need to be lightweight but at the same time withstand the wind force.

The **foundations** models refer to the bill of materials reported in the previous paragraph.

Based on these assumptions, we consider that the main materials responsible for the environmental impacts of the whole wind turbine model are therefore concrete, steel and carbon fibre. The energy consumption and CO_2 emissions for the production of one tonne of concrete, one tonne of steel, and one tonne of carbon fiber (characterisation factors) are reported in Table 1.

The characterization factors for steel and concrete for the CO_2 emissions and embodied energy are taken, in accordance with the MOG2 study, from (Hammond & Jones, 2011). The carbon emissions and energy consumption for carbon fiber was taken from a 2022 study from (Japan Carbon Fiber Manufacturers Association, 2022), also in line with the Mermaid study.

Table 1. Characterization factors for the materials for the turbines and the foundations.

Material	CO_2 emissions [t CO_2 /ton]	Data referring to year	Energy consumption [GJ/ton]	Data referring to year
Steel	1.38	2011	18.8	2011
Concrete	0.19	2011	1.82	2011
Carbon fiber	19.85	2022	350.2	2022

The detailed calculations for obtaining the total energy consumption and CO_2 emissions linked with the production of the different wind turbine parts (separately, not assembled) are reported in Annex 2. Note that the value reported refers to one wind turbine and one foundation per type of foundation. The results are shown in Table 2.

Table 2.Calculated energy consumption and carbon emissions for the production of one 15 MW turbine and the different types of foundations

Component	Material	CO2 emissions [tons CO2 eq]	Energy consumption [GJ]
Blades	Carbon fiber	3871	68289
Nacelle	Steel	1403	19120
Tower	Steel	1187	16168
Monopile foundation	Steel	1819	24778
GBF - concrete	Concrete	2630	25194
GBF - Steel reinforcement	Steel	1452	19781
Jacket foundation	Steel	1380	18800
Jacket Anchoring	Steel	828	11280

The calculation of the CO_2 emissions and energy use for the production of the total turbine with the three foundation types is reported in Section 2.2.

As a reminder:

These calculations are based on rough estimates of the weight of the components, as for the majority of these, technical specifications are not yet available. Additionally, we chose to simplify the model by retaining only the predominant material in the bill of materials. The impacts derived are therefore indicative and preliminary. The purpose is to provide a rough estimate of the energy consumption and emissions associated with the wind farm. The production waste is not accounted for in this assessment.

2.1.2 Transport phase

The transport of the wind turbines and foundations is divided in two phases: a first transport from the production site to a port in Belgium (Oostende), and a second phase where all material is taken to the project area (PEZ) for the construction phase.

Transport from production site to storage port in Belgium

The components of the wind turbines are produced in different locations.

In this study, we assume the wind turbines to be manufactured in the EU. Based on previous experience, it is assumed these are produced in the South of Denmark or North of Germany. Therefore, the average distance to Oostende assumed is 650 km by ship.

Following previous offshore wind farms projects, the jacket foundations and the monopiles are produced in a facility in Hoboken, Belgium (modelled to be at the Smulders plant), at a distance of about 150 km by ship from the Belgian port of Oostende (Smulders Group, 2023). These foundations will thus be shipped from Hoboken to Oostende via ship (using a tugboat and a barge).

As for gravity-based foundations (GBF), these are usually constructed directly on a barge in the closest port, hence the transport distance (to the port) in this case is zero.

Transporting the components of the wind turbines can be done in several ways, including by boat, rail, and truck. However, 15 MW and 22 MW turbines are likely to be transported by boat due to their large size. This is also the case for the foundations. All components that are transported by boat are carried on top of a barge that is pulled by a tugboat. The energy consumption and the CO_2 emissions thus come from the use of this marine vehicle. The tugboat is modelled based on (CROWLEY , 2023) data (Annex 2 – Turbine and Foundations transport data) according to which their machinery generate a total power of 8113 kW, and travel at a speed of 14 knots (~26 km/h). Each barge can carry up to 5 turbines, but we take conservative assumption that 3 turbines are transported per trip (including tower, nacelle and blades), in line with the approach taken in the main EIA report.

The foundations that are transported are also carried on a barge pulled by the same type of tugboat, one at a time.

The energy consumption is calculated multiplying the power of the boat engine for the time that is required for the transport. This is obtained based on the distance travelled and the average speed of the tugboat.

The carbon emissions linked to this are calculated as the emissions of the tugboat. A tugboat burns marine fuel oil, which, according to (DEFRA, 2022) has an emission factor of 0.28 kg CO_{2eq}/kWh (net calorific value). (DEFRA, 2022) is used as a source for emission factors of different fuels as one of the most recent and up-to-date reliable sources. As different types of data and thus approaches are used in the various steps of the life cycle, it is important to have a source of emission factors that provides such number with different units (e.g., kgCO_2/kWh and kgCO_2/kg fuel as well).

A summary of the input data for the calculation for distances and methods is reported in the annexes.

The results of the calculations estimating the energy consumption and the related carbon emissions of the transport from the production site to a port in Belgium (Oostende) are reported in Table 3.

Note that the duration of the transport refers to the transport of one turbine. However, since the barge carries 3 turbines, the total energy consumption and emissions linked with one trip is divided by three.

Table 3. Calculated energy consumption and carbon emissions for the transport of the components from production site to the port of Oostende.

Component	Duration of transport [hours]	Energy consumption [MWh]	CO_2 emissions [ton CO_{2eq}]
Turbine	25.1	67.8	19
Monopile (incl. transition piece)	5.8	46.9	13.3
JF	5.8	46.9	13.3
GBF	0	0	0

Transport from the storage port to the project area

Transport from the port to the project area is done for the turbines, the monopile foundations, the jacket foundations, and the gravity-based foundations separately. Each component (turbines, foundations) therefore needs a different transport line. Once on site they will be assembled in the construction phase. The transport from the port to the project area and the construction phase are intertwined. In this study the transport to the project area of the three foundation types is calculated together with the construction, as recent data on larger wind turbines was only available for the two phases together. This does not change the total impact of the system, as both transport to the project area and construction will be accounted for.

The approach in this 'LCA' study is different from the one of the EIR (refers to "ship movements"). Instead of focusing on the number of movements done, the calculation is done starting from the distance travelled, the time taken, the power specification and fuel type burned by the boat performing the activity.

According to (Zhiyu , 2021), the transport and subsequent construction procedure uses several types of boats and machinery. According to the technical review performed, a tugboat is used to pull barges or other type of machinery (cranes, jack-up barges, etc.), not self-propelling. Tugboats are used due to their lower operational costs and flexibility. Therefore, the transport to the site of the components is modelled using the same type of tugboat as for the transport to the port (engine power of 8113 kW, average speed of 14 knots, or 25.93 km/h) (CROWLEY , 2023).

The project area has a distance from the coastline ranging between 35 km and 55 km: an average of 45 km is used in the calculations. For this distance, using the data on the tugboat reported above, a transfer duration of 1.74 h is calculated.

It should be noted that, due to uncertainties in the number of crew members involved in the transport (and construction) operations, the impacts related to the transport of the crew is not considered in this study.

Based on the above data, the energy consumption and carbon emissions have been calculated for the transport of the turbines (excluding foundations, which are reported together with the installation phase) from the port to the project area and are reported in Table 4. The numbers refer to the transport of one turbine (as for the transport from production site to port, a barge carries 3 turbines, therefore the impact of one round of transportation is divided by 3).

Table 4. Calculated energy consumption and carbon emissions for the transport of parts from storage port to the project area.

Component	Duration of transport (hours)	Energy consumption [MWh]	CO_2 emissions [ton CO_{2eq}]
Turbine	1.7	5	1.3
Monopile	included in construction phase		
JF	included in construction phase		
GBF	included in construction phase		

Considering both transports together, thus from the production site to the project area, the following impact are calculated (Table 5). Note that the impacts of transport of the GBF are zero because of two reasons: (i) the production facility is on location – no transport needed, and (ii) the transport from the port to the project area is calculated together with the construction phase in this study, due to data availability and reliability. The impact of the monopile and the jacket foundation is similar, as both foundations come from the same production site and the calculations are time-based.

Table 5. Calculated energy consumption and carbon emissions for transport of the components from their respective production sites to the project area.

Component	Energy consumption [MWh]	CO2 emissions [ton CO2]
Turbine	72	21
Monopile (including transition piece)	47	13
JF	47	13
GBF	0.00 (included in the construction phase)	0.00 (included in the construction phase)

2.1.3 Construction phase

In general, during the construction phase the parts of the entire wind turbine are assembled and connected to the grid (Zhiang, 2021). The CO_2 emissions and energy consumption of this phase come from using ad-hoc equipment to place the foundations with several activities (e.g., dredging, lifting, hammering, etc.), and positioning and connecting the wind turbine on top. For example, for GBF-based wind turbines, the foundations are placed on the seabed and ballasting is done to ensure the system withstands environmental loads (Esteban, 2015). As for monopiles, these are lifted and installed with a crane, and hammered into the seabed with a large hydraulic hammer. Grouting is also performed to connect the monopile and the transition piece.

For modelling the construction phase, the data from (Li et al, 2022) were used. In their paper, the authors evaluate the environmental impacts of offshore wind farms up to 2040. (Li et al, 2022) outline the several operations needed for installing the three different foundation types, and describe the work time needed for each operation, the type of vessel, and the fuel rate for each vessel.

The emissions are calculated based on the hours of work foreseen and the fuel consumption, using the appropriate conversion factor from (DEFRA, 2022). For the energy consumption, since the power of the vessels used in the paper was not available, the emissions were converted into energy equivalents using (DEFRA, 2022). The detailed results with the activity breakdown are reported in the Annex 3 – Turbine and Foundations construction data Figures are referring to the construction of one turbine.

A summary of the impacts for the construction phase can be found in Table 6.

Table 6. Calculated energy consumption and carbon emissions for the construction of one turbine (15 MW) (data from Li et al., 2022 and (DEFRA, 2022)).

Component	Energy consumption [MWh]	CO_2 emissions [ton CO_2]
Turbine	199.4	54
Monopile (including transition piece)	196.1	54
JF	1224	328
GBF	813.7	223

2.1.4 Operational phase

Similarly, the operational phase has been modelled based on the study from (Li et al, 2022). This study includes the maintenance foreseen for one wind turbine for one year. As the lifespan of the park is considered to be 20 years, the impacts obtained will be multiplied by 20. Both preventive maintenance and corrective maintenance (repair works) are included in this phase. These operations are currently carried out with vessels, ad-hoc vessels (e.g., jack-up vessels) for specific replacement operations, or helicopter. As of today, no primary data (measured on the field on a specific wind farm) are available for operations and maintenance of 15 MW wind turbine (and even more that for 22 MW turbines). For this reason, the uncertainty linked with this phase is high, and one can only go for literature proxies.

Similarly, one must consider the innovations made in maintenance, with improved materials requiring less maintenance, remote inspections technologies, i.e., the use of smart sensors and drones which would help reduce the number of boat trips. Therefore, the current calculated impact is to be considered as a high-level estimation. Nonetheless, they do provide a starting point for the evaluation of the impacts from this life cycle stage.

The waste produced during operations and maintenance (broken or defect equipment, used oils and lubricants, …) is not included in this assessment.

The impact of the operational phase are reported in the Annex 4 – Turbine and Foundations operations and maintenance. A summary of the impacts is reported in Table 7. It should be noted that based on the data, it is assumed that maintenance will be mostly done on the turbine components, rather than on the foundations. For this reason, for this step there is no differentiation among different foundation types.

Table 7. Impacts associated with operations and maintenance of one wind turbine for 20 years of activity.

Activity	Energy consumption [MWh]	CO2 emissions [tons CO2]
Total maintenance 1 year	304	83
Total maintenance 20 years	6075	1666

2.1.5 Decommissioning phase

The decommissioning phase comprises of all those operations required to disassemble the turbines on location, remove the foundations, and restore the seabed. The decommissioning phase also comprises the recovery of materials (steel, concrete, carbon fibre) from re-use and recycling the components of the wind farm.

Different types of foundations will require different decommissioning operations: in this study the impact from the dismantling phase is assumed to be the same as the impact for the installation phase, due to the similarities in the activities performed. This causes the decommissioning stage to generate carbon emissions and energy use.

On the other hand, the decommissioning phase involves also re-use (e.g., components that can be reused in other turbines can be used as spare parts, other can be refurbished, etc.), re-purpose (e.g., the blades can be used to make other objects, e.g., in an entertainment park or as architecture structure) and recycling (e.g., steel, copper, etc.) of the wind turbines' components and foundations.

The assumption made in this study is that, with the evolving regulation requirements and technologies, these re-use, re-purpose, recycling activities will enable to (partially) offset the production of new materials. In other words, the impact from the activities performed when removing the infrastructure from the sea could be offset by re-using or recycling the components (assumption similar to (IMDC , 2014)).

Under this assumption, the decommissioning phase is considered energy and carbon neutral.

A detailed balance (outside project scope) to understand the contribution of this decommissioning phase would be needed to understand under which conditions the impact stemming from the removal of the infrastructure is offset by the materials recovery (share and efficiency of re-use or recycling, distance from recycler, market conditions for the sales of the materials, technology used to manufacture equivalent materials from virgin sources, etc.).

2.2 Conclusion – 15 MW turbine with 3 foundation types

In this section, the total emissions for the turbines with the three types of foundations are reported (Table 8).

Table 8. Calculated energy consumption and carbon emissions during the lifecycle of one 15MW turbine per type foundation.

	Energy consumption [GWh]			Carbon footprint [ton CO_2]		
	Monopile	Gravity Based	Jacket	Monopile	Gravity Based	Jacket
Production	35.65	41.26	37.13	8280	10543	8669
Transport	0.12	0.07	0.12	34	21	34
Installation	0.4	1.01	1.42	108	277	382
Operations and Maintenance	6.1	6.1	6.1	1666	1666	1666
Decommissioning	*0*	*0*	*0*	*0*	*0*	*0*
Total life cycle (20y)	42.2	48.4	44.7	10088	12507	10751

3 Inter-array cabling in the PEZ

Cabling infrastructure are an important part of a wind farm: often their contribution is not considered in LCA studies of offshore wind energy, as the focus is on the turbines and the foundations. However, studies show that these contribute considerably to the total energy consumption and carbon emissions of the total park (IMDC , 2014), (Bonou, Laurent, & Olsen, 2016).

The main cables considered in PEZ project are of two types: inter-array cables, that are needed to connect the turbines with each other and to the main offshore station MOG2, and larger export cables delivering the electricity generated from MOG2 to shore. This study is only concerned with the first type of cables, i.e. inter-array, the ones used to connect the turbines to MOG2. The export cables are not in the scope but have been considered in (IMDC, 2022).

The life cycle stages of the cables are similar to those of a turbine: first a manufacturing stage produces the cables, then these are transported and installed (usually these two activities are carried out by the same vessel), then during their lifespan maintenance operations are carried out, and finally decommissioning takes place at the end of their life. In this study, the lifespan considered for the cables is the same as that for the turbines, i.e., 20 years, as the project requires that everything be removed from the project area upon decommissioning.

3.1 Life cycle assessment of the 66 kV cables

In addition to the technical specifications and the lifespan, we define a reference length of the cables. The reference for this study is based on cable infrastructures required per 15 MW turbine.

The total cable length to be used in the park according to the GIS modelling is divided by the number of 15 MW turbines foreseen in the park. In total (considering the three parts of the project area) ca. 620 km of cables are to be used, and a total of 210 turbines (15 MW) are to be installed. Therefore, it is calculated that 2.95 km of cables will be needed per turbine. Thus, the impacts will be calculated referring to 2.95 km of cables.

The cables considered in this study are typical submarine cables used in wind farms, i.e., 66 kV, three-core cables with a steel wire armour and a fiber optic cable embedded. In particular, this study models these cables from ABB's XLPE cables and previous IMDC studies (IMDC , 2014).

Based on data from (IMDC , 2014), the bill of material for the 66 kV cables is reported in Annex 5 – Cables (66 kV inter-array) production data.

3.1.1 Production phase

Production is assumed to be carried out in the ABB facility in Västerås, South of Sweden. The cable specifications used to calculate the impact of production have been reported in the section above.

The impact of cable production follows the same logic as the approach used for the turbine manufacturing: the energy consumption and CO_2 emissions for the production of the cable are considered, and then scaled to the length of cabling per turbine (2.95 km of cable per turbine). To ease the calculations, the impacts are calculated first referring to 1 km of cable, as reported in Table 9.

Based on bill of materials and values for energy consumption and carbon emissions per constituting material (see Annex 5 – Cables (66 kV inter-array) production data), the calculated energy consumption for 1 km 66kV cable equals 1.31 GWh and the CO_2 emissions amount to 363.15 tonnes of CO_2.

Table 9. Calculated energy consumption and carbon emissions for the production of 1 km of 66kV inter-array cable.

Material	Mass for 1 km of cable [ton] (IMDC , 2014) (ABB, 2011))	Energy consumption [GJ]	CO_2 emissions [ton CO_2]
Aluminium conductor	9.3	1463.9	148.5
Conductive PE	1.1	79.3	1.4
XLPE insulator	4.1	296.0	5.2
Copper screen	31.2	1464.1	127.7
Protection around the individual ores (HDPE)	2.1	150.1	2.6
Galvanised steel	23.3	603.8	42.0
Bitumen	2.6	12.7	0.8
Polypropylene 50%	4.4	212.4	5.7
Carbon fiber reinforced plastic	0.0	4.0	0.2
PE in fiber optic cable	1.7	162.4	4.4
Copper in fibre optic cable	6.1	284.4	24.8
Total for 1 km of cable	85.7	47744.2	363.2

When considering the length of cable of 2.95 km per turbine, the energy consumption and CO_2 emissions for the 66kV inter-array cable per turbine are calculated to be 3.88 GWh and the 1,070.43 tons CO_{2eq}.

3.1.2 Transport phase

In this phase the transport of the cables from the production location to the project area is considered. The cables are transported directly from the production facility in Sweden to the project area on a cable-laying boat, modelled based on the fleet from (JAN DE NUL, 2023), running on diesel. To be as close as possible to the technologies likely to be used at the time of project realisation, the boat chosen for this step is the latest available from the fleet of Jan De Nul Group, and thus different from boat references used in previous similar studies (mostly in the capacity of the boat).

The distance travelled is estimated to be 1100 nautical miles, or 2037 km.

This boat carries a total of 10,700 ton of cable, has a propulsion power of 6,000 kW (with two engines of 3,000 kW) and travels at an average speed of 12.5 knots (23.15 km/h). The total travel time is therefore assumed to be 88 h.

Given the cable specifications outlined in the introductory part of this chapter, 1 km of cable weighs 85.68 tons. Considering the total capacity of the boat, 124.88 km of cables can be carried on one load.

The energy consumption is therefore calculated from the power used and the total travel time, being in total around 528 MWh. For 2.95 km of cables, that is, the length of cable per turbine calculated for this offshore wind project, the energy consumption is estimated to be around 12.5 MWh. The carbon emissions are calculated on the basis of the emission factor of Defra for burning marine fuel oil, i.e., 0.28 kg CO_{2eq}/kWh (net calorific value) (DEFRA, 2022). With this value, the emissions are calculated to be around 150 tons CO_{2eq} per trip, which renders 3.54 tons CO_{2eq} per 2.95 km of cable (see Table 10)

Table 10. Calculated energy consumption and carbon emissions for the transport of 2.95 km of 66kV inter-array cable.

Distance travelled [km]	Average speed [km/h]	Duration of the trip [hours]	Ship propulsion power [kW]	Energy consumption for [MWh]	CO_2 emissions [ton CO_{2eq}]
2037	23.2	88	6000	12.5	3.5

3.1.3 Construction phase

The cables are installed with jetting. This is the usual technique used for laying cables connecting among them offshore wind turbines.

For laying cables by means of jetting, a cable-laying boat is used (modelled after the Isaac Newton boat from Jan De Nul Group). A technical datasheet for the ship assumed to be used in these operations is available in Annex 261.9. Leveling of the seabed is not considered in the scope of this study.

The speed of jetting is assumed to be approximately 1.65 km per day (in line with previous studies, (DEFRA, 2022). The power used by the boat is assumed to be 60% of the total installed marine fuel oil (MFO) power of the boat, i.e., 7398 kW. With these assumptions, for laying 1 km of cable, 14.55 h are required.

The total power required for laying 2.95 km of cables, that is, the amount of cable calculated per turbine, is 317.2 kWh.

Considering an emission factor of MFO of 0.28 kg CO_{2eq}/kWh (net calorific value), a total of 90.1 tons of CO_{2eq} are emitted during this stage.

The results are reported in Table 11.

Table 11. Calculated energy consumption and carbon emissions for the installation of 2.95 km of 66kV inter-array cable.

Jetting speed [km/day]	Boat power (used for installation) [kW]	Time required for laying 2.95 km of cable [hours]	Energy consumption [MWh]	CO_2 emissions [ton CO_{2eq}]
1.7	7398	42.9	317.2	90.1

3.1.4 Operational phase

The operational phase includes all those activities performed during the life cycle of the cables in order to prevent damage and power interruptions by promptly fixing faults when these occur (corrective maintenance)[1]. Maintenance is fundamental in ensuring the maximum operativity of the wind farm, thus its economic sustainability.

The maintenance activities during the lifetime of the cables are represented by corrective operations and repairing works done on failing cables. This figure is highly variable and depends on what the fault is, where it is located, how often it occurs, what equipment the maintenance company uses, etc. Estimating the energy consumption and emissions from repair works over a lifespan of 20 years is therefore a challenge. Currently, not many studies report the hours spent or the operations required to do for an offshore wind farm. A study from (Birkeland, 2011) estimates the carbon emissions of maintenance operations (mainly related to fuel used for inspections and maintenance) to be 31.5 % of the total impacts per MW.km of cabling infrastructure for inter-array cables, having a lifespan of 40 years. Based on this assumption, we calculate the total of CO2 emissions of the 33 kV cabling to be equal to (production, transport and construction/0.685) = 576.54 tons per km of cable for 40 years. Applying 31.5% of this being 181.61 ton of CO_2, which is then divided by 2 for 20 years and multiplied by 2.95 km for the functional unit. This renders total emissions for corrective maintenance for 20 years of about 267.66 tons CO_2.

[1] Preventive maintenance is not included in the scope of this study due to uncertainties with this operation.

Using the same approach for calculating the energy consumption, with a characterisation factor of 0.28 kg CO_{2eq}/kWh (net calorific value) (DEFRA, 2022), a total of ca. 922 MWh are used in 20 years.

Table 12. Calculated energy consumption and carbon emissions for the operations of 2.95 km of 66kV inter-array cable (with 20 years lifespan).

Activity	Energy consumption [MWh]	CO_2 emissions [tons CO_2]
Corrective maintenance (repair works)	942	267

3.1.5 Decommissioning phase

Decommissioning includes all those activities to dig up the cables and restore the seabed. As decommissioning is done at the end of the lifespan of the cables, and since few offshore wind farms have already reached this stage, there is little to no empirical environmental data on this phase of the life cycle.

However, the operations involving the decommissioning will have an important impact, as they entail digging out the cables from the seabed and restoring it. For this, a first estimation is that of considering the impact to be the same as the impact of the installation operations, as they would be carried out with similar equipment.

Following a similar approach as in (IMDC , 2014), also done in the case of the turbine due to lack of ad-hoc decommissioning data, this phase is considered carbon neutral on the basis that the impacts arising from the operations performed to remove the cables from the seabed are offset by the gains from re-using or recycling the materials.

3.2 Conclusion – total cabling for one wind turbine

The total lifecycle energy consumption and CO_2 emissions of the inter-array cabling related to one 15 MW wind turbine (2.95 km of cable), from production to decommissioning, is reported in the following Table 13.

Table 13. Calculated energy consumption and carbon emissions for the lifecycle of 2.95 km of 66kV inter-array cable (with 20 years lifespan).

	Energy consumption [GWh]	CO_2 emissions [tons CO_2]
Production	3.9	1070.4
Transport	0.01	3.5
Installation	0.3	90.1
Operations and Maintenance	0.92	261.9
Decommissioning	-	-
Total life cycle	5.13	1426

4 Wind farm and cabling total impacts

4.1 22 MW offshore wind turbine

While the calculations above refer to a 15 MW offshore wind turbine, the environmental impact assessment report considers the possibility of using turbines up to 22 MW of power. The assumption is that the wind farm configuration will be based on 15 MW and 22 MW turbine in 2 scenarios.

22 MW turbines construction and operational data are not available yet, as these turbines are not yet produced by manufacturers. Thus, instead of a bill of material approach (based on figures from a spec sheet), a scale up approach of the calculation results above is followed.

Scaling up a system must account for the several factors that could deviate from a simple linear extrapolation. For instance, the size of the turbine, or the amount of material needed might not follow the same proportions as the power output (e.g., if the turbine is more efficient in delivering power, then the power-to-mass may change). For this study, reference studies addressing the relationship between turbine and foundations size are used.

This scale-up factor for the turbine is based on a publication by (Kim, 2021). In their paper, the authors provide a mathematical approach to calculate the dimensions of an upscaled turbine, starting from existing designs, based on empirical observations. Thereby, using the dimensions of a 15 MW turbine, we derive those for a 22 MW by applying upscaling formulas.

For the scale-up of the foundations, a different source is used, due to availability limitations. According to (Roach, 2023), offshore foundations scale-up from 15 MW to 20 MW, 25 MW, and 30 MW in general by a factor of 0.75 when considering the power of the turbines and applying a hydrodynamic model. This model does have its limitations in being applied to the PEZ case, as the hydrodynamic model is best suited for semi-submergible foundations. However, it does give an indication on how the mass of the foundations could increase when scaling up the system, thus, it is still used to estimate the impacts.

It should be noted that the evaluation of the impacts of the 22 MW turbines and related foundations will also require to calculate the impacts starting from the amount of materials that are used. The upscaling factor allows to calculate the mass of components of the larger system, from which the impacts will be derived with the same method as reported in the 15 MW case. The upscaling factor is a number that is calculated starting from the nominal power of the turbines (see Table 14). This scaling factor is subsequently used to scale up each component of the turbine (blades, nacelle, tower) separately, using different formulas. This is needed as different components might increase in size differently. The formulas used for the upscaling of the individual parts are reported in Table 14.

It should also be noted that the transport and construction, the operation and maintenance, and the decommissioning phases are assumed not to be affected by the scale up of the system. This assumption is supported by the fact that the modelling is done basing it on the time that is required to perform those activities, and this is modelled to not be dependent on the size of the system. In particular, it is assumed that the bargeboard will have the same carrying capacity (3 turbines) also in the case of the larger 22 MW turbines. This is because it is assumed that if three larger turbines do not fit on the same barge as the 15 MW, then a larger barge will be used, but the same tugboat will be used to pull it.

Thus, in our assumptions, the scaling-up mainly affects the production step, as more materials will be required to produce larger components.

Table 14. Upscaling of one wind turbine from 15 MW to 22 MW.

Turbine upscaling	Unit		Formula
Size of the original turbine (P_0)	MW	15	
Size of the upscaled turbine (P)	MW	22	
S_t (turbine scale factor)	-	1.21106	$(P/P_0)^{1/2}$
22 MW Turbine	**Unit**		**Formula**
Rotor diameter 22 MW	m	291	$R_{rot0} * S_t$
Hub height 22 MW	m	201	$H_{hub0} - R_{rot0} + R_{rot1}$
blade mass	t	105	$M_{blade0} * S_t^{2.5}$
nacelle mass	t	1580	$M_{nacelle0} * S_t^{2.3}$
tower (hub) mass	t	1388	$M_{hub0} * S_t^{2.5}$
Total mass of 22 MW	t	3073	

The foundations are also scaled up based on the initial mass, considered to be the one of 15 MW turbine foundation, that is increased with a factor 0.75.

Table 15. Parameters for the 22 MW turbine related foundations.

Foundations upscaling	Unit	Value	Material
Upscaling factor		0.75	
Monopile foundation			
Monopile mass for 22 MW turbine	t	2307	Steel
Jacket foundation			
Jacket foundation mass	t	1750	Steel
Anchoring	t	1050	Steel
Gravity-based foundation			
GBF mass – concrete	t	24225	Concrete
GBF mass – reinforcement	t	1841	Steel

Considering the parameters above, the impacts for the 22 MW turbine can be calculated. The results are reported in Table 16.

Table 16. Calculated energy consumption and carbon emissions during the lifecycle of a 22 MW turbine with different type of foundations.

	Energy consumption [GWh]			Carbon footprint [ton CO_2]		
	Monopile	Gravity Based	Jacket	Monopile	Gravity Based	Jacket
Production	58.2	68.0	60.7	13525.9	17486.7	14206.9
Transport	0.1	0.1	0.1	33.9	20.6	33.9
Installation	0.4	1.0	1.4	107.9	276.9	382.1
Operations and Maintenance	6.1	6.1	6.1	1666.5	1666.5	1666.5
Decommissioning	0	0	0	0	0	0
Total life cycle (20y)	64.8	75.1	68.4	15334.2	19450.7	16289.4

4.2 Complete wind farm impacts

Impact assessment

The following chapter reports the impacts of the complete wind farm, considering the configurations and scenarios delineated in the main environmental impact assessment. For a detailed description of the scenarios, please refer to the main EIR study.

In the scenarios developed, the PEZ is made of three lots: PE I, PE II, PE III. PE I has a nominal installed capacity of 700 MW, while PE II and PE III have a nominal installed capacity of 1400 MW. For each of the three zones, two scenarios have been developed to evaluate the impacts based on the type of turbines used. For each scenario, a scenario “bis” is also developed. The difference between the scenarios and their “bis” lies in the types of foundations assumed to be used. More details below.

In scenario 1 and 1 bis for all three lots, 15 MW turbines are used. It should be noted that the scenarios delineated in the main report are based on a 12-13 MW turbine. As the approach of the LCA was to go for a realistic worst-case scenario, it was deemed a more realistic scenario to go for the 15 MW impacts. In both these scenarios, for PE I, 54 turbines are used; for PE II, 107 turbines are used; and in PE III, 108 turbines are used. These turbines are connected by 143 km of cables in PE I, by 210 km of cables in PE II, and by 266 km of cables in PE III. In all three lots, for scenario 1, 0% of turbines are built with a monopile foundation, 90% use a Jacket foundation, and 10% use a GBF. For scenario 1 bis, 100% of turbines have a monopile foundation, thus 0% have a JF and 0% have a GBF. These parameters are reported in Table 17.

Table 17. Parameters for the three lots in scenario 1 and 1 bis.

	PE I		PE II		PE III	
Common parameters for both scenario 1 and scenario 1 bis						
Parameter	**Value**	**Unit**	**Value**	**Unit**	**Value**	**Unit**
Total nominal capacity	700	MW	1400	MW	1400	MW
Turbine power	15	MW	15	MW	15	MW
Number of turbines	54	-	107	-	108	-
Cables length	143	km	210	km	266	km
Scenario 1						
Monopile	0%	-	0%	-	0%	-
JF	90%	-	90%	-	90%	-
Gravity-based	10%	-	10%	-	10%	-
Scenario 1 bis						
Monopile	100%	-	100%	-	100%	-
JF	0%	-	0%	-	0%	-
Gravity-based	0%	-	0%	-	0%	-

For scenario 2 and scenario 2 bis, 22 MW turbines are used for all three lots, in line with the main environmental impact report. Larger turbines mean less of them to install the same total capacity. In PE I, 32 turbines are needed. In PE II, 64 turbines are needed. In PE III, 64 turbines are needed. The length of the cables is assumed to be the same as for scenario 1, i.e., 143 km for PE I, 210 km for PE II, and 266 km for PE III. The same distribution of foundation types as for scenario 1 and 1 bis is used. I.e., for scenario 2, 0% monopile, 90% jacket, 10% gravity based, and for scenario 2 bis, 100% monopile, 0% JF and 0% GBF. The parameters for scenario 2 and 2 bis are reported in Table 18.

Table 18. Parameters for the three lots in scenario 2.

	PE I		PE II		PE III	
Common parameters for both scenario 2 and scenario 2 bis						
Parameter	**Value**	**Unit**	**Value**	**Unit**	**Value**	**Unit**
Total nominal capacity	700	MW	1400	MW	1400	MW
Turbine power	22	MW	22	MW	22	MW
Number of turbines	32	-	64	-	64	-
Cables length	143	km	210	km	266	km
Scenario 2						
Monopile	0%	-	0%	-	0%	-
JF	90%	-	90%	-	90%	-
Gravity-based	10%	-	10%	-	10%	-
Scenario 2 bis						
Monopile	100%	-	100%	-	100%	-
JF	0%	-	0%	-	0%	-
Gravity-based	0%	-	0%	-	0%	-

Based on these parameters, and based on the impact per turbine (and in the case of the cabling, adapted per km) from Section 2.2 (for 15 MW turbines), Section 4.1 (for 22 MW turbines), and Section 3.2 (for cables), the following total impacts for the PEZ wind farm are obtained (Table 19). The impacts refer to the entire lifetime of the wind farm, i.e., 20 years.

Table 19. Calculated energy consumption and carbon emissions during the lifetime of the wind park (20 years) for the two Scenarios considered.

Scenario	Turbine power	Number of turbines	% Monopile foundations	% Jacket Foundations	% Gravity-Based Foundations	Total CO2 emissions [ktons CO2]	Total energy consumption [GWh]
PE I - 700 MW							
Scenario 1	15	54	0%	90%	10%	658	2683
Scenario 2	22	32	0%	90%	10%	418	1691
Scenario 1 bis	15	54	100%	0%	0%	614	2527
Scenario 2 bis	22	32	100%	0%	0%	392	1599
PE II - 1400 MW							
Scenario 1	15	107	0%	90%	10%	1271	5193
Scenario 2	22	64	0%	90%	10%	800	3251
Scenario 1 bis	15	107	100%	0%	0%	1181	4880
Scenario 2 bis	22	64	100%	0%	0%	747	3066
PE III - 1400 MW							
Scenario 1	15	108	0%	90%	10%	1309	5335
Scenario 2	22	64	0%	90%	10%	827	3348
Scenario 1 bis	15	108	100%	0%	0%	1218	5020
Scenario 2 bis	22	64	100%	0%	0%	774	3163

When considering PE I, PE II, and PE III together the following impacts are calculated (Table 20).

It should be noted that when considering 100% monopile foundations (scenario bis), both the CO2 emissions and the total energy consumption are slightly lower than when considering the scenario with the combination of foundation types (0% MP, 90% JF, and 10% GBF).

Table 20. Impacts of the entire wind farm, considering PE I, PE II, and PE III together.

Total PE I + II + III	Total CO2 emissions 20 y [ktons CO2]	Total energy consumption 20 y [GWh]
Scenario 1	3239	13211
Scenario 2	2046	8290
Scenario 1 bis	3013	12428
Scenario 2 bis	1913	7828

Energy balance

The energy balance is the difference between the energy generated in 20 years by the entire wind farm and the energy consumed necessary to produce, build, and maintain the farm operational for this lifetime.

The entire energy generated by the park is taken from the LCOE study performed by 3E on the PEZ zone (3E, 2021) and is equivalent to 14,930 GWh/year (relative to 15 MW turbines). It should be noted that this number is theoretical and depends on the sea and wind conditions, as well as on the characteristics of the wind turbines. Given that this number was used to assess the LCOE for the PEZ zone, it was used in this study as well.

The figure refers to a 3.5 GW wind farm, made of 1x700 MW lot, and 2x1400 MW lots, which corresponds to our scenarios. Based on this, it is possible to evaluate the theoretical energy generated by each lot per year. The results are reported in Table 21.

Table 21. Calculation of the energy output of the three lots over 1 year and over 20 years.

Lot in PEZ	Nominal capacity [MW]	% of total	Energy produced in 1 year [GWh]	Energy produced in 20 years [GWh]
PE I	700	20%	2986	59720
PE II	1400	40%	5972	119440
PE III	1400	40%	5972	119440
Total	3500	100%	14930	298600

As the nominal energy generated is the same regardless the size of the turbine used, the same values are used in both scenarios. Small variations will occur due to the different turbines' characteristics, however, the significance when comparing it to the energy consumption is small, thus acceptable.

Using the above-calculated values for the energy generated and the impacts obtained in Section 4.2, the following energy balance can be drawn (Table 22).

Table 22. Energy balance for 20 years for the PEZ wind farm.

Scenario	Total energy generated in 20 y [GWh]	Total energy required in 20 y [GWh]	% energy required over energy generated
PE I - 700 MW			
Scenario 1	59720	2683	4%
Scenario 2	59720	1691	3%
Scenario 1 bis	59720	2527	4%
Scenario 2 bis	59720	1599	3%
PE II - 1400 MW			
Scenario 1	119440	5193	4%
Scenario 2	119440	3251	3%
Scenario 1 bis	119440	4880	4%
Scenario 2 bis	119440	3066	3%
PE III - 1400 MW			
Scenario 1	119440	5335	4%
Scenario 2	119440	3348	3%
Scenario 1 bis	119440	5020	4%
Scenario 2 bis	119440	3163	3%

5 Annexes

Annex 1 – Turbine and Foundations production data

15 MW offshore wind turbine

Parameter	Unit	Value	Main material
Rotor diameter	m	240	-
Blade length	m	117	-
Hub height (from sea level)	m	150	-
Hub diameter	m	8	-
Total tower height	m	180	-
Blade mass	t	65	Carbon fiber
Nacelle mass	t	1017	Steel
Tower mass	t	860	Steel

Source: (NREL, 2020)

22 MW offshore wind turbine

Turbine upscaling	Unit		Formula
Size of the original turbine (P_0)	MW	15	
Size of the upscaled turbine (P)	MW	22	
S_t (turbine scale-up factor)	-	1.2	$(P/P_0)^{1/2}$

22 MW Turbine	Unit		Formula
Rotor diameter 22 MW	m	291	$R_{rot0} * S_t$
Hub height 22 MW	m	201	$H_{hub0} - R_{rot0} + R_{rot1}$
blade mass	t	105	$M_{blade0} * S_t^{2.5}$
nacelle mass	t	1580	$M_{nacelle0} * S_t^{2.3}$
tower (hub) mass	t	1388	$M_{hub0} * S_t^{2.5}$
Total mass of 22 MW	t	3073	

Monopile foundation data

Monopile foundation for a 15 MW turbine	Unit	Value	Material
Monopile mass for 15 MW turbine	t	1318	Steel

Monopile upscaling	Unit	Value	Material
Upscaling factor		0.8	
Monopile mass for 22 MW turbine	t	2306.5	Steel

Jacket foundation data

Jacket foundation source data	Unit	Value
Jacket foundation structure (source A) **(NREL, 2016)**	tons	1013
Jacket foundation structure (source B) **(Durakovic, 2022)**	tons	1200
Jacket foundation structure (source C) **(IBERDROLA, 2023)**	tons	845
Jacket foundation structure (source D) **(IBERDROLA, 2023)**	tons	625
Anchoring (1 steel pole 40m tall * 2.5m diameter - not full) **(IBERDROLA, 2023)**	tons	150

Jacket foundation parameters for a 15 MW turbine	Unit	Value	Materials	Notes
Jacket foundation mass	tons	1000	Steel	Estimated based on JF sources detailed in the above table
Anchoring	tons	600	Steel	Based on Wikinger offshore farm

JF upscaling	Unit	Value
Upscaling factor		0.8
Jacket foundation mass	tons	1750
Anchoring	tons	1050

Gravity-based foundation data

Gravity based foundation data	Unit	Value	Label
GBF for a 15 MW turbine			
Truncated cone height	m	20	H2
Cylinder height	m	20	H1
Outer diameter - top of shaft	m	22	d
Outer diameter - bottom conical part	m	42	D
Diameter base	m	45	Bd
Bottom base height	m	1	H3
Slanted height cone	m	22.4	
Area (surface) cylinder	m2	1382.3	
Area (surface) truncated cone	m2	4013.5	
Total area cylinder + truncated cone	m2	5395.8	
Thickness steel layer	m	0.025	
Thickness cement layer	m	1	
Volume cylinder + truncated cone steel	m3	134.9	
Volume cylinder + truncated cone cement	m3	5395.8	
Volume base cement	m3	141.4	
Density steel	kg/m3	7800	
Density concrete	kg/m3	2500	
GBF mass - concrete	t	13843 (~14000)	Concrete
GBF mass - reinforcement	t	1052 (~1100)	Steel

GBF upscaling

Parameters	Unit	Value	Material
Upscaling factor		0.8	
GBF mass - concrete	t	24225.2	Concrete
GBF mass - reinforcement	t	1841.3	Steel

Annex 2 – Turbine and Foundations transport data

Distances

Transport distances from production side to Oostende port			
Component	Value	Unit	Assumptions
Turbine	650	km	The production of the turbines is assumed to take place in south of Denmark
Monopile (including transition piece)	150	km	Produced in Belgium (Hoboken)
JF	150	km	Produced in Belgium (Hoboken)
GBF	0	km	Produced directly on storage port

Component	Value	Unit	Assumptions
Turbine	45.0	km	The project area spans from 35 km to 55 km from the coast. An average of 45 km is chosen
Monopile (including transition piece)	0.0	km	Included in the installation phase
JF	0.0	km	Included in the installation phase
GBF	0.0	km	Included in the installation phase

Transport modes

Transport methods				
Method	*power [kW]*	*average speed [knots]*	*average speed [km/h]*	*Capacity [n of turbines]*
Tugboat	8113	14	**25.9**	3

The characterization factor considered for the fuel used in the tugboat is 0.28 kg CO_{2eq}/kWh (net calorific value) (DEFRA, 2022).

Annex 3 – Turbine and Foundations construction data

Energy consumption and CO_2 emissions calculation for the construction of foundations.
Source: Li et al, 2022

Activity	Description	Equipment	Fuel type	Work time [h]	Fuel rate [l/h]	Energy consumption [MWh]*	CO2 emissions [tons CO2]**
GBF							
Substrate clearance	Transport of excavator	Barge	HFO	72	100	77.6	22.0
	Dredging	Excavator	Diesel	72	0	0.3	0.1
	Disposal of substrate material	Barge	HFO	70	100	75.4	21.4
Substrate replacement	Transport of rock	Vessel	HFO	8	100	9.1	2.6
	Dumping of rock	Vessel	HFO	72	100	77.6	22.0
	Transport of foundation	Tugboat	Diesel	135	323	437.1	116.2
	Transport of jack-up	Tugboat	Diesel	2	323	5.8	1.5
	Construction of foundation	Jack-up vessel	HFO	24	170	44.0	12.5
Scour protection	Transport of rock	Vessel	HFO	8	100	9.1	2.6
	Dumping of rock	Vessel	HFO	72	100	77.6	22.0
Total						813.7	223.1
Monopile							
Driving pile	Transportation of pump/generator	Barge	HFO	24	100	258.6	7.3
	Injection of grout	Pump/generator	Diesel	24	185	445.6	11.8
Construction	Tugboats for transport of foundations	Tugboat	Diesel	10	323	332.5	8.8
	Transport of jack-up	Tugboat	Diesel	4	323	116.6	3.1
	Construction of foundation	Jack-up vessel	HFO	24	170	439.7	12.5
Scour protection	Transport of rock	Vessel	HFO	5	100	55.3	1.6
	Dumping of rock	Vessel	HFO	29	100	312.5	8.9

Activity	Description	Equipment	Fuel type	Work time [h]	Fuel rate [l/h]	Energy consumption [MWh]*	CO2 emissions [tons CO2]**
Total						1960.9	54.1
Jacket							
Driving pile	Transportation of pump/generator injection of grout	Barge	HFO	24	100	25.9	7.3
	Injection of grout	Pump/generator	Diesel	72	185	133.7	35.5
Construction	Tugboats for transport of foundations	Tugboat	Diesel	144	323	466.3	123.9
	Transport of jack-up	Tugboat	Diesel	144	323	466.3	123.9
	Construction of foundation	Jack-up vessel	HFO	72	170	131.9	37.5
Total						1224.0	328.3
*Characterisation factor CO2 emissions **(DEFRA, 2022)** [kgCO2 / kWh] for MFO is 0.28 and for diesel is 0.27							
Characterisation factor CO2 emissions **(DEFRA, 2022)[kgCO2 / liters fuel] for HFO is 3.1 and for diesel is 2.7							

Energy consumption and CO_2 emissions calculation for the construction of the turbine.
Source: Li et al, 2022

Description	Equipment	Fuel type	Work time [h]	Fuel rate [l/h]	Characterisation factor CO2 emissions (DEFRA, 2022) [kgCO2 / kWh]	Characterisation factor CO2 emissions (DEFRA, 2022) [kgCO2 / liters fuel]	Energy consumption [MWh]	CO2 emissions [tons CO2]
Transport jack-up	Tugboat	Diesel	48.00	322.60	0.26582	2.6681	**155**	**41.3**
Assembly wind turbine	Vessel	HFO	24.00	170.00	0.28413	3.0619	**44.0**	**12.5**
							199	**53.8**

Annex 4 – Turbine and Foundations operations and maintenance

Energy consumption and CO_2 emissions calculation for operations and maintenance activities for one turbine.

Source: (Li et al, 2022)

Activity	Description	Equipment	Fuel type	Work time [h]	Fuel rate [l/h]	Energy consumption [MWh]	CO_2 emissions [tons CO_2]
Preventive maintenance	Regular inspection of turbines	Vessel	Diesel	60	262.5	**158.0**	**42.0**
Corrective maintenance	Irregular inspection and repair	Vessel	Diesel	0.48	262.5	**1.3**	**0.3**
	Irregular inspection and repair - airborne	Helicopter	Diesel	4	83.1	**3.3**	**0.9**
Corrective maintenance	Replacement of nacelle - vessel	Vessel	HFO	24	100	**25.9**	**7.4**
	Replacement of nacelle - jack-up vessel	Jack-up vessel	HFO	24	170	**44.0**	**12.5**
	Replacement of blades - vessel	Vessel	HFO	24	100	**25.9**	**7.4**
	Replacement of blades - jack-up vessel	Jack-up vessel	HFO	24	170	**44.0**	**12.5**
	Replacement of small components - vessel	Vessel	HFO	0.48	100	**0.5**	**0.2**
	Replacement of small components - jack-up vessel	Jack-up vessel	HFO	0.48	170	**0.9**	**0.3**
Total for 1 year						**303.8**	**83.3**
Total for 20 years						**6074.9**	**1666.5**

Annex 5 – Cables (66 kV inter-array) production data

Bill of materials for the 66 kV cables used in the Prinses Elisabeth-zone (PEZ), according to (IMDC , 2014). Source: (ABB, 2011).

Material	Quantity for 1 km of cable [m3]	Density [kg/m3]	Mass for 1 km of cable [kg]	Mass for 1 km of cable [ton]
Aluminium conductor	3.4	2755	9311.9	9.3
Conductive PE	1.1	970	1086.4	1.1
XLPE insulator	4.2	970	4054.6	4.1
Copper screen	3.5	8900	31150	31.2
Protection around the individual ores (HDPE)	2.1	970	2056.4	2.1
Galvanised steel	2.9	7930	23314.2	23.3
Bitumen	2.5	1050	2583	2.6
Polypropylene 50%	4.6	946	4380.0	4.4
Carbon fiber reinforced plastic	0.01	1800	17.3	0.02
PE in fiber optic cable	1.8	946	1674.4	1.7
Copper in fibre optic cable	0.7	8900	6052	6.05
Total mass 1 km cable			85680.2	85.7

Characterization factors for energy consumption and CO2 emissions per constituting material.

Material	Energy consumption per tonne of material [GJ/ton]	CO_2 emissions per tonne of material [ton CO_2/ton]
Aluminium conductor	157.2	15.9
Conductive PE	73	1.3
XLPE insulator	73	1.3
Copper screen	47	4.1
Protection around the individual ores (HDPE)	73	1.3
Galvanised steel	25.9	1.8
Bitumen	4.9	0.3
Polypropylene 50%	97	2.6
Carbon fiber reinforced plastic	234	11.5
PE in fiber optic cable	97	2.6
Copper in fibre optic cable	47	4.1

Sources for the characterization factors for energy consumption and CO2 emissions.

Material	Source energy consumption factor	Source CO_2 emissions factor
Aluminium conductor	(Peng, 2022)	(Peng, 2022)
Conductive PE	(Nicholson, 2021)	(Nicholson, 2021)
XLPE insulator	(Nicholson, 2021)	(Nicholson, 2021)
Copper screen	(ICA)	(ICA)
Protection around the individual ores (HDPE)	(Nicholson, 2021)	(Nicholson, 2021)
Galvanised steel	(Galvanize it! , 2023)	(Galvanize it! , 2023)
Bitumen	IMDC, 2014	IMDC, 2014
Polypropylene 50%	(Nicholson, 2021)	(Nicholson, 2021)
Carbon fiber reinforced plastic	IMDC, 2014	IMDC, 2014
PE in fiber optic cable	(Nicholson, 2021)	(Nicholson, 2021)
Copper in fibre optic cable	(ICA)	(ICA)

Annex 6 – Cables (66 kV inter-array) transport data

Parameter	Description	Value	Unit	Value converted	Unit	Source
Distance	Distance travelled by boat	1100.0	NM	2037.2	km	https://www.bednblue.com/sailing-distance-calculator
Power of boat	2*2000 kW propulsion power	6000.0	kW			(JAN DE NUL, 2023)
Speed of boat		12.5	knots	23.2	km/h	(JAN DE NUL, 2023)
Capacity of boat		10700.0	ton	-	-	(JAN DE NUL, 2023)
Weight of 1 km of cable		85.7	ton	-	-	-
km of cable the boat can carry		124.9	km	-	-	-
Time travelled		88.0	h	-	-	-

The emission factor used for the boat running on MFO is 0.28 kg CO_{2eq}/kWh (net calorific value) (DEFRA, 2022).

Annex 7 – Cables (66 kV inter-array) construction data

Parameter	Value	Unit	Source
Jetting speed	1.7	km/day	IMDC, 2014
Boat power for installation	7398.0	kW	(JAN DE NUL, 2023)
Total boat power	12330.0	kW	(JAN DE NUL, 2023)
Total time to lay 1km of cable	14.6	h	-

The emission factor used for the boat running on MFO is 0.28 kgCO2/kWh (DEFRA, 2022).

Annex 8 – Cables (66 kV inter-array) operations and maintenance data

Description	Equipment	Fuel type	Power of vessel [kW]	Energy consumption [kWh]	CO_2 emissions [tons CO_2]	Source
Corrective maintenance for 1 km for 40 years	Vessel	Diesel	unknown	625480.1	177.7	(IMDC , 2014) (Birkeland, 2011)
Corrective maintenance for cables for 1 turbine for 40 years				1843677.2	523.8	
Corrective maintenance for cables for 1 turbine for 20 years				921838.6	261.9	

Annex 9 – Technical data of shipping used in the study

Tugboat (Crowley)

Reference: https://www.crowley.com/wp-content/uploads/sites/7/2021/04/ocean_Tugs-2021-New.pdf

GENERAL SPECIFICATIONS

FLAG
United States

PORT OF REGISTRY
Lake Charles, LA

BUILDER
Bollinger Shipyards - Amelia, LA

OVERALL DIMENSIONS
Length: 146' (44.4m) Ocean Wind/Ocean Wave
156' (47.5m) Ocean Sky/Ocean Sun
Breadth: 46' (14.03m)
Depth: 25' (7.62m)
Design Draft: 21' (6.4m)

TONNAGE - <1600GRT

CONSTRUCTION - Steel

OPEN DECK SPACE
47' x 45' 2115 sq2
13.71M x 14.32M 196.48 sq m2

FUEL CAPACITY
208,000 Gallons (787m³) Ocean Wind/Ocean Wave
218,000 Gallons (825m³) Ocean Sky/Ocean Sun

FUEL OIL OVERFLOW - 2,118 gal. (8.02m³)

DIRTY OIL - 1,153 gal. (4.36m³)

OILY WATER - 1,225 gal.(4.64m³)

HYDRAULIC OIL - 570 gal (2.16m³)

FRESH WATER
19,060 gal. (72.15m³) Ocean Wind/Ocean Wave
24,700 gal. (93.5m³) Ocean Sky/Ocean Sun

GRAY WATER - 6,474 gal. (24.51m³)

SEWAGE HOLDING - 5,582 gal. (21.13m³)

FOAM STORAGE - 1,436 gal. (5.44 m³)

LUBE OIL - 2,900 gal. (10.98m³)

MAIN ENGINES
(2) Caterpillar C-280-12 Tier II*
Developing 10,880 (8,113kW) Total BHP

HARBOR GENERATOR
(1) 340kW Caterpillar C-18 Tier II*

EMERGENCY GENERATOR
(1) 125kW Caterpillar C-6.6 Tier II*

SHAFT GENERATORS
(2) 1,475 KVA Ocean Wind/Ocean Wave
(2) KATO rated 1.5MW each Ocean Sky/Ocean Sun

PROPELLERS
(2) 4 Blade Cu-Ni-Al CPP
153.5" (3.9m) Diameter

NOZZLES - High Efficiency

REDUCTION GEARS
(2) Reintjes LAF 5666

SPEED - 14 Knots

BOW THRUSTER
(1) Berg (Electric) VFD 850HP Ocean Wind/Ocean Wave
(2) Berg (Electric) VFD 500HP Ocean Sky/Ocean Sun

STERN THRUSTER
(1) Berg 500HP - Ocean Sky/Ocean Sun

CRANES
Aft Deck SWL 3,850 lbs.

BOLLARD PULL - CONTINUOUS
Ocean Wave 162 ST / 147.0 MT
Ocean Wind 165 ST / 149.7 MT
Ocean Sun 160 ST / 145.5 MT
Ocean Sky 161 ST / 147.0 MT

TOWING WINCH
Intercon - DW275 Hydraulic
Min. Holding Power 350 S.T. (317.51 M.T.) • 500,000lbs (226.80 MT) @ 20 Ft/Min (6.1m/Min)

INDEPENDENT DECK AUXILIARY TUGGER WINCH
300 ft. of 7/8" wire rated at 25,000lbs.

WIRE GUIDE PINS - 200 MT Triplex

INDEPENDENT AUXILIARY WIRE DRUM
300'of 1" Wire rated @ 40,000 Lbs (18.14 MT) @ 100 Ft/Min (30.48 m/Min)
Independent Capstan
Rated @ 23,000 Lbs (10.43 MT) Line Pull @150 Ft/Min (45.72 m/Min)

BOW WINCH
Intercon - VMS Winch
Electric Windless Mooring 1.25" chain
Independent Capstan
Line Drum 300' of 1.75" Quantum-8

TOWING WIRES
3,000' (914m) - 2.5" (63.5mm) Wire (Upper)
4,000' (1,219m) - 2.75"(69.85mm) Wire (Lower)

SHARK JAWS - 350 MT Triplex Quick Release

STERN ROLLER - 6' (1.83m) Diameter

ACCOMMODATIONS
13 total - (3) 1 person, (5) 2 person staterooms; 14 total - (2) 1 person, (6) 2 person staterooms

NAVIGATION/ COMMUNICATIONS EQUIPMENT
(2) Radar, (2) GPS, GMDSS, Autopilot, Gyrocompass, Depth Sounder - SOLAS Approved, (5) Radios, World Phone, (2) EPIRB, Dynamic Positioning

CLASSIFICATION
A1, Towing Service, AMS, ABS, ABS DP-1 Ocean Wind/Ocean Wave, ABS DP-2 Ocean Sky/Ocean Sun, USCG Certificate of Inspection, Green Passport, SOLAS, International Load Line Certificate

DP1 only specs listed in red / DP2 only in blue

All information contained herein (including but not limited to any specifications, particulars, capacities, or capabilities) is believed to be correct, but is not guaranteed and is subject to change without notice.

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Barge (Crowley)

Reference: https://www.crowley.com/wp-content/uploads/2018/10/Crowley-Barge-455-Series-Spec-Sheet.pdf

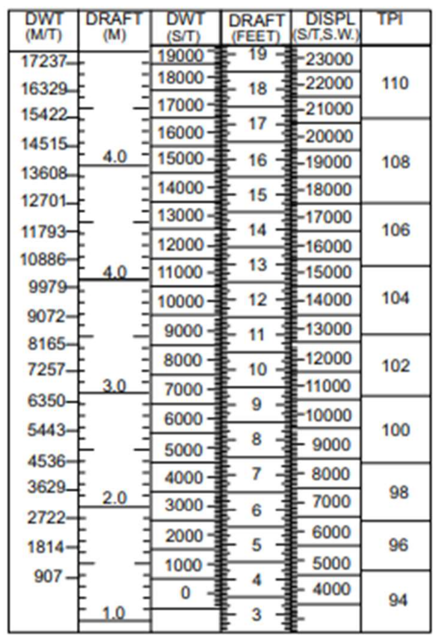
455 Series - 400' x 105' x 25' - 121.92 m x 32.00 m x 7.62 m

Specifications

Summer Load Line Keel Draft	19' 1.1875"	5.82 m
Summer Load Line Displacement	23,090 ST	20,946.90 MT
Summer Load Line Deadweight	19,226 ST	17,441.53 MT
Lightship Draft (mean)	3' 9"	1.14 m
Lightship Displacement	3,863.87 ST	3,505.24 MT
Lightship LCG Forward of Transom	202.22'	61.64 m
Lightship VCG Above Baseline	13.81'	4.21 m
Draft Mark Locations - Forward of Transom		
Fwd Marks	337.77'	102.95 m
Aft Marks	60.83'	18.54 m

Longitudinal Strength Data

Maximum Allowable Still Water Bending Moments		
In Port	345,117 LT-ft	106,880 MT-m
At Sea	157,468 LT-ft	48,766 MT-m
Maximum Allowable Still Water Shear Force		
In Port	3,276 LT	3,328.57 MT
At Sea	1,781 LT	1,809.58 MT



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Cable-laying boat (Jan De Nul Group)

Reference: https://www.jandenul.com/sites/default/files/2022-09/Isaac%20Newton%20%28EN%29.pdf

DP2 Cable Laying / Trenching Support Vessel

TECHNICAL SPECS	
Deadweight	12,500 t
Turntable capacity	5,000 t + 7,400 t
Length o.a.	138 m
Breadth	32 m
Draught loaded	7.3 m
Dynamic positioning	DP2
Propulsion power	2 x 3,000 kW
Bow thruster power	2 x 1,500 kW
Retractable thruster power	2,000 kW
Total installed diesel power	12,330 kW
Bollard pull	100 t
Speed	12.5 kn
Notation	Strengthbottom
Accommodation	75
Built in	2015

In the Cable Laying mode, the vessel can install up to 10,700 t of cable and is thereto equipped with a 7,400 t capacity turntable above deck and a 5,000 t capacity turntable below deck along with two tensioners of 20 t or as required by the project, chute and auxiliary equipment.

SPECIFICATIONS OF THE TURNTABLES	ABOVE DECK	UNDER DECK		
Capacity	7,400 t	5,000 t	Max. speed at inner diameter	900 m/h
Inside outer basket diameter	27.4 m	23.5 m	Ramp up to max. speed	45 s
Inner basket diameter	8 m	4.6 m	Loading tower tensioner	5 Te
Basket wall height (open structure)	8.5 m	4.5 m	Deck tensioner	20 Te

SPECIFICATION OFFSHORE KNUCKLE BOOM ACTIVE HEAVE COMPENSATION CRANES	AFT CRANE		FORE CRANE
	Main	Aux	Main
Capacity	500 kN @ 15 m	50 kN @ 35 m	250 kN @ 15 m
	350 kN @ 35 m		100 kN @ 35 m
Max AHC load	350 kN @ 35 m	25 kN @ 35 m	100 kN @ 35 m
Waterdepth	200 m	200 m	200 m
Personnel handling		Yes	Yes

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