Thor Offshore Wind Farm

Offshore project description

Thor Wind Farm I/S

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Contents

0. List of abbreviations

Table 0.1: List of abbreviations and associated terms described in the project description.

Abbreviation	Term
AtoN	Aid to Navigation
CFE	Controlled Flow Excavation
CLV	Cable-Laying Vessel
CPS	Cable Protection System
CTV	Crew Transfer Vessel
dB	Decibel
DEA	Danish Energy Agency
DP	Dynamic Positioning
EIA	Environmental Impact Assessment
EPA	(Danish) Environmental Protection Agency
HAT	Highest Astronomical Tide
HLV	Heavy Lift Vessel
ICCP	Impressed Current Cathodic Protection
IPS	Intermediate peripheral structure
ISV	Installation Support Vessel
kV	Kilovolt
m/s	Meters per second
MGO	Marine Gas Oil
MSL	Mean Sea Level
MSBL	Mean Sea Bed Level
MW	Megawatt
OWF	Offshore Wind Farm
PE	Polyethylene
PLGR	Pre-lay grapnel run
ROV	Remotely Operated Vehicle
SOV	Service Operation Vessel
TSHD	Trailing Suction Hopper Dredger
TSV	Trenching Support Vessel
UXO	Unexploded Ordnance
XLPE	Cross-linked Polyethylene

1. Introduction

As part of the Danish Parliament's Energy Agreement of 29 June 2018, the Danish Energy Agency (DEA) agreed to the construction of three new 800–1,000 MW offshore wind farms (OWF), to be completed prior to 2030. Subsequently in 2019, the DEA initiated a screening study of Danish territorial waters to identify suitable sites for OWF development, from which the Thor Offshore Wind Farm (Thor OWF) was identified. According to the agreement, the site for Thor OWF is to be located in the North Sea, offshore Nissum Fjord and the coastal town of Thorsminde, at a distance of at least 20 km and will be constructed and fully operational latest 31st December 2027. Thor Wind Farm I/S, owned by RWE, has been awarded the Concession Agreement for the construction and connection of Thor OWF – with a capacity of 1,000 MW – to the 220 kV grid at Volder Mark, while Energinet is responsible for the conversion of the 220/400 kV substation at Idomlund.

Prior to offshore works commencing, an environmental impact assessment (EIA) of the offshore Thor OWF project must be completed in accordance with Section III of the Danish Environmental Assessment Act. The project is also covered by section 1(2) no.1 of executive order no. 1476 (BEK nr 803 af 14/06/2023), which relates to impact assessments concerning international nature conservation sites and the protection of certain species.

In order to carry out an offshore EIA for Thor OWF, a comprehensive technical project description is needed which allows for an assessment of possible environmental impacts relating to construction, operation and maintenance, and decommissioning activities. This project description thus contains descriptions for the range of anticipated technical solutions concerning all installation activities, associated waste streams and emissions, as well as key components of the wind turbines and foundations, an offshore substation and inter-array and export cabling. This document describes the offshore part of the project that Thor Wind Farm I/S intends to implement, with the purpose of providing a detailed project description which can therefore serve as the technical foundation for the environmental impact assessment for the 1,000 MW Thor OWF project.

This offshore project description for Thor OWF contains detailed technical descriptions of the infrastructure and activities associated with construction, commissioning, operation and decommissioning for all offshore components. The project description does not consider any technical elements or activities occurring as part of the onshore project. The boundary between the onshore and offshore project is defined by the highest daily water level at the coastline. Thus, all facilities, infrastructure and activities located seaward of the highest daily water level forms part of the offshore project.

This document has been authored by NIRAS based on information provided by Thor Wind Farm I/S.

2. Thor OWF site and layout

The Danish Energy Agency has in 2018 and 2020 conducted screenings of the wind energy potential in Danish marine waters (COWI, 2018; COWI, 2020). Preliminary screening identified a 440 km^2 area in the Danish North Sea, which, following the completion of a strategic environmental assessment supported by a series of site investigations conducted in 2019–2020, was further delineated to a 286 km^2 area suitable for the construction of Thor OWF (Figure 2.1).

The preliminary investigations and the strategic environmental assessment identified various parameters which the delineation of Thor OWF accounts for. These included the identification of stone reefs, the presence of an important gravel deposit, proximity to a key shipping route west of the park area, consideration of various fishing grounds, consideration of different bird species, and potential cumulative effects arising in relation to the nearby wind farm projects Vesterhav Nord and Vesterhav Syd (Energistyrelsen, 2021).

Once completed, Thor OWF will comprise 72 14 MW wind turbines, an offshore substation platform, inter-array cables connecting the turbines to the substation and two export cables through which the transformed electricity will be carried to land (Figure 2.1). Thor OWF will be located approximately 22 km off the west coast of Jutland, Denmark and once built, will have a maximum installed capacity of 1,000 MW and a total project area not exceeding 220 km^2. This corresponds to a turbine density of 4.54 MW/km^2.

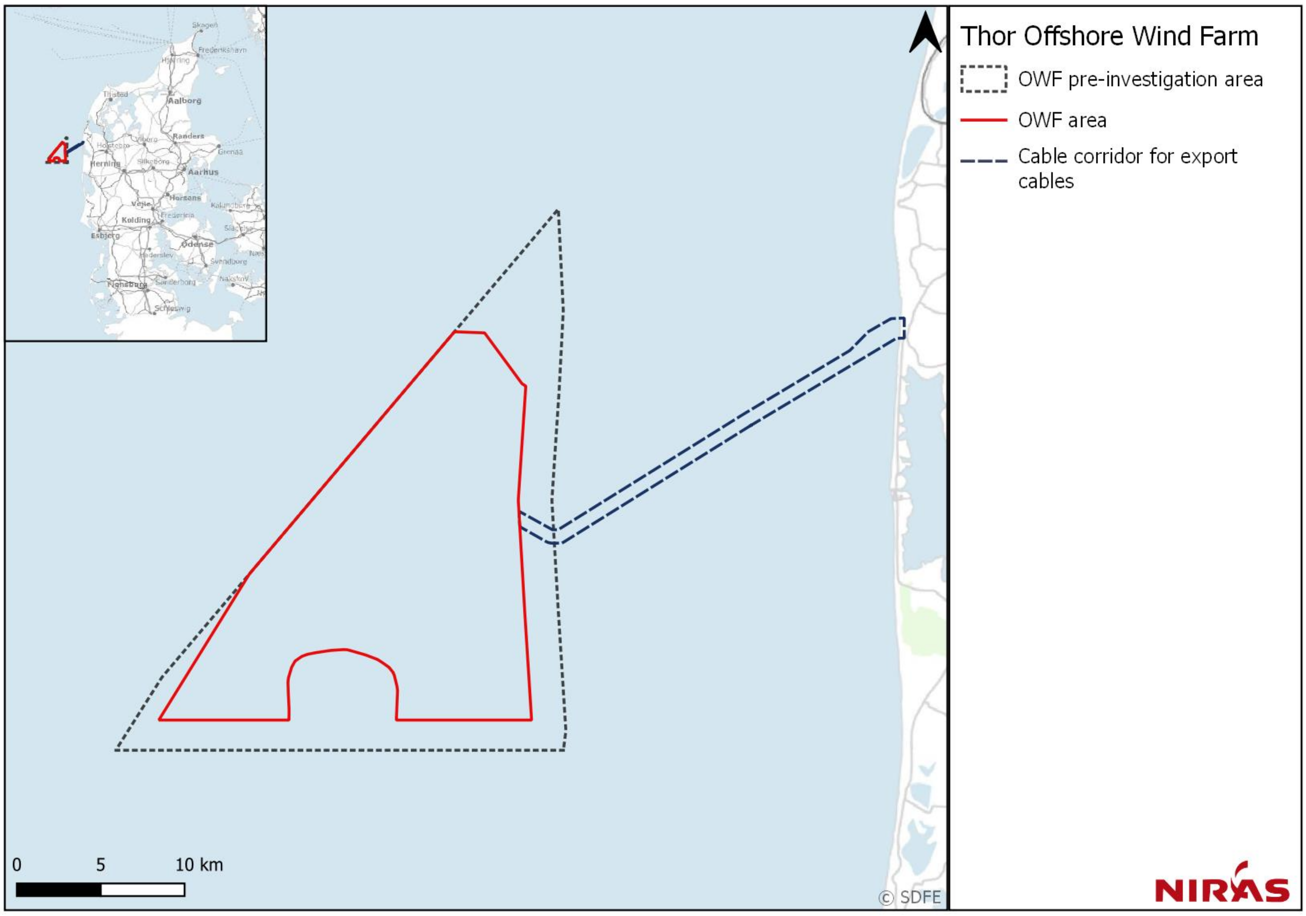

Figure 2.1: Total project area for Thor OWF displaying the area for the wind farm (OWF area) and export cable corridor. The total project area is 286 km^2 while the pre-investigation area is 440 km^2.

2.1 Physical and metocean characteristics

The project area for Thor OWF is located in the Danish North Sea with water depths ranging between 20.5–32 m (Figure 2.2). The seabed within the OWF area is dominated by sand, with areas of coarse sand, gravels and boulders, as well as smaller areas with clay and stone reefs, while boulders are found predominantly in the northern and western part of the OWF area (MTT, 2020a). The export cable corridor displays water depths of between 1.8 m to 30 m, with sediments characterised by sands, gravels and diamicton (MTT, 2020b).

Site-specific meteorological and oceanographic (Met-Ocean) analyses have been conducted for Thor OWF. The Met-Ocean characteristics are based on state-of-the-art numerical and statistical hydrodynamic and spectral wave models known as the DHI Danish Waters Model, which describe both normal and extreme weather conditions expected in the Thor OWF area. The data includes wave height, current speed, wind speed and direction etc.

Current speeds within Thor OWF average 0.1 m/s and the seabed displays abundant sand waves and ripples, indicating highly mobile sediments (DHI, 2020). Winds speeds across Thor OWF average 9 m/s and 10.5 m/s measured 10 m and 100 m above sea level respectively, with a west-east and northwest-southeast wind direction prevailing (DHI, 2020).

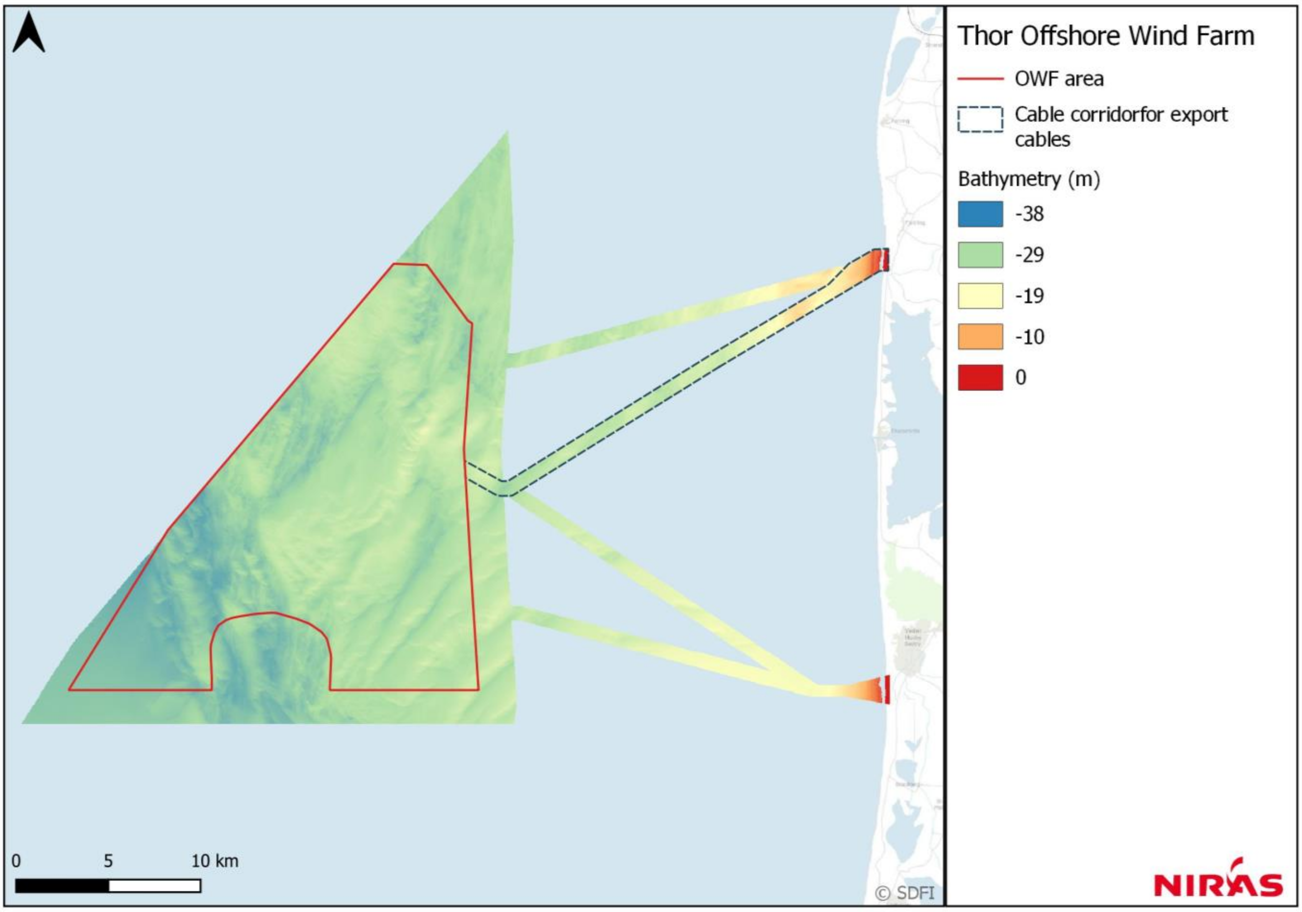

Figure 2.2: Local bathymetry (1 m resolution) across the Thor OWF area. Bathymetry ranges from approximately 22–32 m.

3. Project summary

This chapter provides a short summary of the various project elements for Thor OWF, including the wind turbines and their foundations, an offshore substation as well as inter-array and export cables. An overall project timeline for off-shore construction and installation is also provided.

3.1 Wind turbines and foundations

Thor OWF will have a maximum installed capacity of 1,000 MW allowing for 72 14 MW wind turbines. The location of the 72 sites investigated for turbine placement are shown in Figure 3.1.

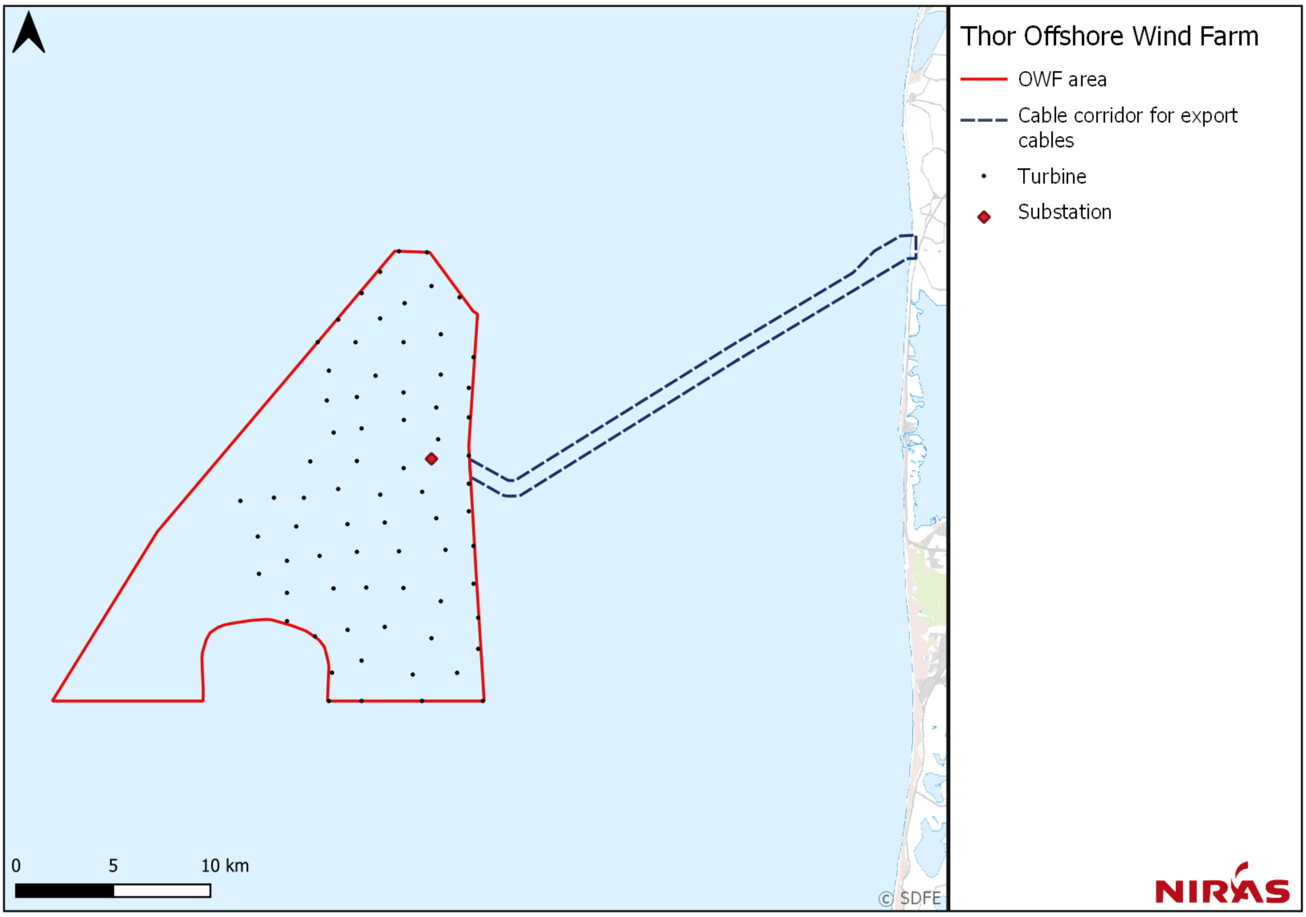

Figure 3.1: Indicative layout for 72 14 MW turbines. The location of the offshore substation and the export cable corridor are also shown.

The wind turbines will have a rotor diameter of 236 m and a hub height of 148 m, resulting in a total tip height of 266 m. The wind turbines will be located toward the eastern part of the Thor OWF project area to account for the parameters identified during preliminary investigations and the strategic environmental assessment (see section 2). The wind turbines will be attached to steel monopile foundations (section 5) approximately 65–105 m long, which will be driven into the seabed via piling.

The coordinates for each individual wind turbine position and the position of the offshore substation presented in Figure 3.1 can be found in Appendix 1.

3.2 Offshore substation platform

An offshore substation (section 6) will collect, stabilise and transform the electricity generated from the individual wind turbines into a higher voltage prior to exporting the power to land. The offshore substation comprises a topside platform containing two 275/66 kV transformers, switchgears, earthing transformers and a back-up power source, as well various operational facilities (e.g. control room), navigation and aviation light control, fire suppression, rainwater separation and communication antennas. The substation will be remotely operated but will be able to accommodate a normal working team of 4–6 persons and will be equipped with a heli-hoist platform, two boat landings and two pairs of access points for motion compensated gangways. The foundation used for the offshore substation will be a post-piled jacket.

3.3 Offshore cables

66 kV AC inter-array cables (section 7) will connect the wind turbines via a series of 16 arrays which will be routed to the offshore substation platform and onto the cable deck. The inter-array cables will comprise three cores consisting of an aluminium conductor and an armour layer surrounded by insulating material and will have a total diameter of approximately 120–195 mm. The total length of inter-array cabling required for Thor OWF is approximately 205 km.

Two 275 kV AC submarine export cables (section 8) will carry the generated electricity from the offshore substation platform to landfall east of Volder Mark, where they will be connected to a transition joint bay on or east of the beach. The export cables will comprise three cores consisting of aluminium or copper conductors surrounded by insulating material encased within an armour layer and surrounded by an outer protective sheath. The export cables will have a diameter of between 282–305 mm and will each have a length of approximately 30 km.

3.4 Project timeline

The offshore construction of Thor OWF will start in 2024 and the wind farm is expected to be in full operation by the end of 2026. An overall timeline for major activities related to the offshore construction and installation is provided in Table 3.1.

Table 3.1: Timeline for major activities related to the construction and installation of Thor OWF with 72 14 MW turbines, a substation and two export cables. The OWF is expected to be in full operation by the end of 2026.

	2024		2025				2026				Approximate total duration (weeks)
Construction and installation	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	
Seabed preparation											5
Offshore substation											18
Turbine foundation											22
Scour protection											22
Inter-array cables											18
Export cables											22
Turbines											40

4. Wind turbines

4.1 Description

Based on a maximum installed capacity of 1,000 MW, Thor OWF will comprise 72 turbines with an individual capacity of 14 MW (with the possibility to boost). The selected wind turbine is Siemens SG DD-236+ with direct drive (no gear-box). Each wind turbine comprises a steel tower, a nacelle and three blades (Figure 4.1), with the exact dimensions and appearances of the wind turbines dependent on the manufacturers design.

The nacelle houses a generator, which converts the mechanical energy of the three-bladed rotor to electric energy. The rotor blades will turn clockwise, when viewed from the windward direction and will have a diameter of approximately 236 m (Figure 4.1). The nacelle is placed on top of a tower, which will be attached to a foundation to secure it to the seabed. The turbines begin generating power when the wind speed at hub height is 3 m/s. The turbine power output increases with increasing wind speed and the wind turbines typically achieve their rated output at wind speeds between 12.5 and 14 m/s at hub height. The design of the turbines ensures safe operation, such that if the average wind speed exceeds 28–30 m/s for extended periods, the turbines shut down automatically.

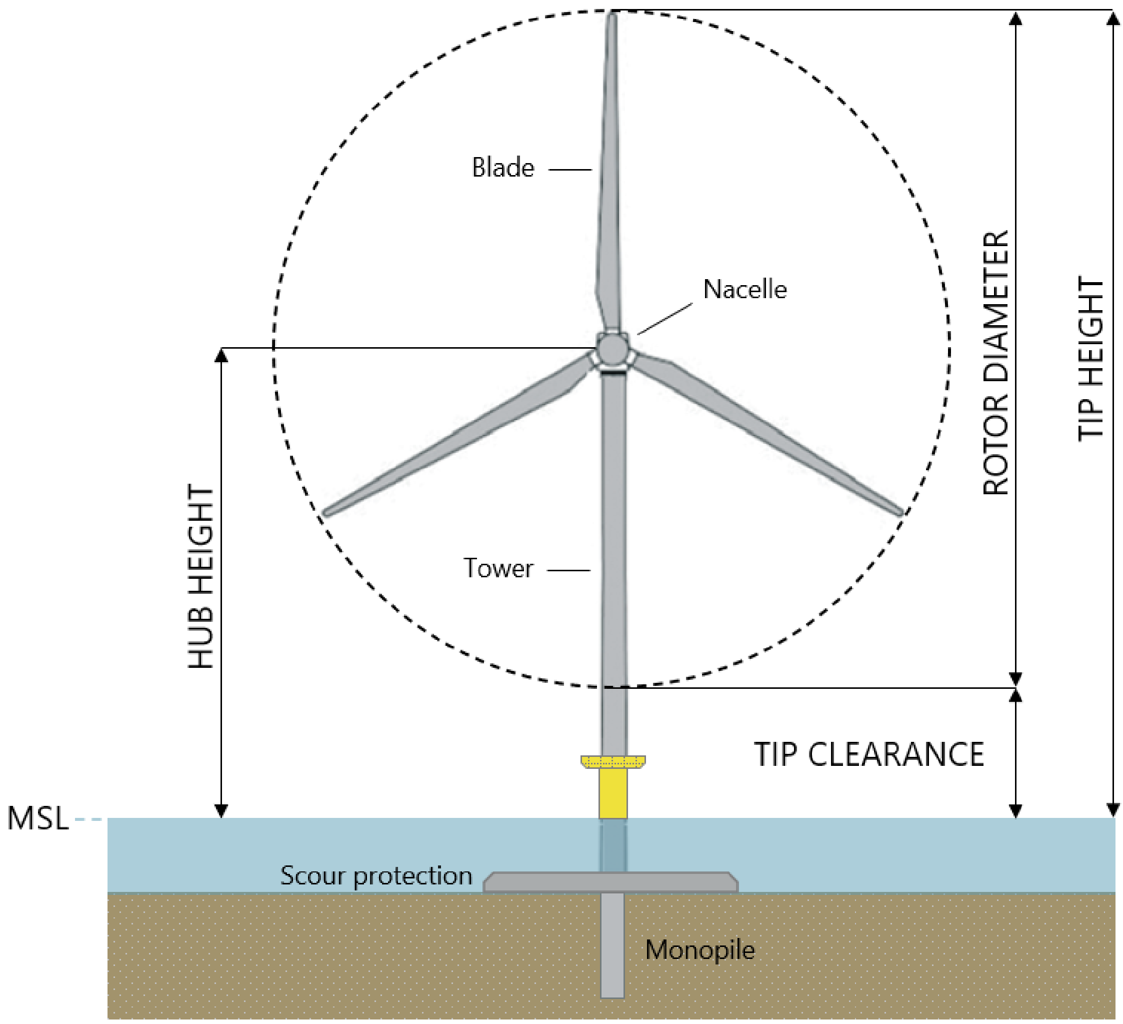

Figure 4.1: Illustration of a typical offshore wind turbine with blades, nacelle, tower, monopile foundation and scour protection. Visual explanations of hub height, tip clearance, rotor diameter and tip height are included for reference.

4.2 Dimensions

The dimensions of the turbines considered for the Thor OWF are summarised in Table 4.1.

The distance between the highest astronomical tide (HAT) and the lower wing tip, termed the tip clearance, must be at least 20 meters to ensure safety of navigation for mariners (Danish Maritime Authority). Based on the rotor diameter and hub heigh, the tip clearance will be 30 meters. Furthermore, offshore wind turbines with a height of 100 m or more above MSL must be reported to, and approved by, the Danish Civil Aviation and Railway Authority.

Table 4.1: Dimensions of the 14 MW turbines considered for Thor OWF. The tip clearance will be 30 m (the distance between the lower wing tip and the highest astronomical tide).

Dimensions	14 MW wind turbine
Rotor diameter (m)	236
Tip height (m)	266
Hub height above MSL* (m)	148
Rotor swept area (m^2)	43,743
Nacelle (length x width x height) (m)	22x11x12 – 29x12x12

** MSL = Mean sea level*

4.3 Materials

The main type and weight of raw materials constituting the 14 MW turbines are summarised in Table 4.2.Recyclable blades will be used on 40 of the 72 wind turbines, while green steel will be used on half of the towers (RWE, 2023).

Table 4.2: Type and weight of primary raw materials used in a 14 MW turbine. The weight is specified for material used for one turbine. The materials listed comprise approximately 98 % of the total mass of a typical turbine (NREL, 2017).

Material type	Component	Approx. weight (metric ton)
Copper	Hub	12–16
Aluminium	Hub	14–18
Cast iron	Hub	230–250
Fiberglass, reinforced epoxy	Blades	55–65
Steel	Tower; hub	800–900

4.4 Oils and fluids

Wind turbines contain lubricants and hydraulic oils within the different components. The estimated quantities for the turbine considered for the Thor OWF are listed in Table 4.3. The design of the wind turbines ensures that potential lubricant spills from the various components are contained.

Table 4.3: Estimated quantities of fluids and lubricants present in 14 MW turbines.

Fluid type	Approximate quantities (in litres)
Hydraulic oil	850
Yaw/pitch motor oil	240
Transformer oil	6,500

4.5 Colour

The turbines blades, nacelle and the tower will be painted a light grey colour (RAL 7035). The lower section of the tower from MSL and up to a height of 15 meters (relative to HAT), or up to the height of the navigational markings if positioned higher than 15 meters, will be painted yellow, as described in Annex 3.2.1 of the Concession Agreement. The colour RAL 1023 (traffic yellow) is recommended (IALA, 2021).

4.6 Lighting and marking

The wind turbines must exhibit permanent lighting and markings of a distinguishing character, and which are visible to both vessels and aircraft in accordance with requirements set out by the Danish Maritime Authority and Danish Civil Aviation and Railway Authority.

4.6.1 Lighting for aviation

Thor OWF will be marked on appropriate aeronautical charts, as required by the Danish Civil Aviation and Railway Authority (Trafikstyrelsen). Aviation marking of the turbines will be in accordance with the rules set out in the regulations and guidelines for civil aviation for offshore windfarms (BL 3-11 2. udgave af 28/04/2014, 2014; Trafikstyrelsen, 2021).

The distance between the turbines along the perimeter of Thor OWF ranges from approx. 1400 m to >3 km. Following consultation with Danish Civil Aviation and Railway Authority, Thor OWF will follow the aviation marking requirements described for stand alone offshore wind tubines, meaning that all 72 wind turbines will be marked using medium intensity nacelle lighting and low intensity tower lightsThe specific aviation marking requirements for the Thor OWF consists of:

- Two medium intensity flashing lights comprising white lights (20,000 candela) for daytime hours and red lights (2,000 candela) during nighttime positioned on all 72 wind turbines. The lights must be placed at the top of the nacelle and be visible 360° horizontally around the wind turbine and visible regardless of the blades position.
- In addition to the two nacelle lights, all wind turbines must also be marked with three fixed low-intensity red lights (of at least 32 candela), placed at the same height around the middle of the tower.

As set out in the regulations and guidelines for civil aviation for offshore windfarms (BL 3-11 2. udgave af 28/04/2014, 2014; Trafikstyrelsen, 2021), visibility meters can be used to regulate the light intensity of the aviation markings using measured meteorological visibility. For aviation lighting at or above 2000 candela, the intensity will be adjusted under the following conditions during the operation phase of Thor OWF:

- to 30% if measured visibility is between 5–10 km;
- to 10% if the measured visibility is greater than 10 km.
- If visibility is 5 km or under, aviation lights must be set at 100%.

The intensity of the aviation markings will be regulated based on the worst measured visibility at Thor OWF.

4.6.2 Lighting and markings for maritime navigation

Offshore wind turbine foundations require Aids of Navigation (AtoN) consisting of lighting and markings to ensure safety of maritime navigation. AtoNs must comply with Annex 3.2 and Annex 3.2.1 in the Concession Agreement and will be agreed with the Danish Maritime Authority prior to initiation of construction.

To ensure safe maritime navigation around Thor OWF, turbines at the wind farm perimenter will be fitted with yellow synchronous flashing lanterns (Fl(3)Y10s) with an effective illuminating power of at least five nautical miles. Lanterns will be visible 360° around the turbine to ensure visibility from all directions. Lanterns should be placed near the main access platform level, although there are no specific height requirements for AtoNs. The distance between the lanterns should not exceed 2 nautical miles (IALA, 2021).

Reflective identification consisting of numbering/lettering must be placed on each wind turbine structure, either on the tower, directly onto the foundation or on the access platform using a sign or panel. The numbers/letters must be 0.5–1 m in size and must consist of black letters on a yellow background. The specific proposal must be approved by the Danish Maritime Authority.

4.7 Installation of wind turbines

Prior to installation of the wind turbines, the various components of the nacelle, tower sections and blades will be transported from the manufacturer to the pre-assembly and load-out port at Esbjerg, where they will be preassembled onshore. The individual turbine components will then be loaded onto a jack-up installation vessel.

The legs of the jack-up vessel are lowered vertically until contact is made with the seabed in order to stabilise the vessel. Once stabilised, the individual turbine components will be transferred from the quayside onto the main deck using the main crane system. The turbine components will be sea-fastened (fixed for seagoing transportation) before the installation vessel jack down. The vessel will receive clearance to leave port and depart for the Thor OWF site. Upon arrival at the site, the installation vessel will travel to the intended location for turbine installation.

Once at the Thor OWF, the installation vessel will jack up and prepare for individual wind turbine installation, whereby the jack-up legs will penetrate 5-25 m into the seabed based on preliminary site data, depending on punch through risk at individual locations. This will be verified at a later stage once site investigation is completed, and vessel providers are able to make a final Leg Penetration Assessment (LPA). The footprint for each jack-up vessel leg is approximately 360-560 m^2.

The turbine components will be lifted by crane from the main deck onto the intended foundation. The position of the components will be fixed, and thereafter the lifting operations will cease and the installation vessel will jack down and proceed to the next location to repeat the procedure.

Once all turbine components that were loaded onto the installation vessel have been installed, the vessel will return to the load-out port to commence the next installation cycle.

4.7.1 Installation time schedule

The installation of the wind turbines will be completed over a period of approximately 9-10 months and will require 1-2 jack-up vessels operating 24 hours a day. All timeframes are based on a P50 schedule, which represents the most likely scenario.

4.8 Commissioning of wind turbines

The commissioning of the wind turbines will be carried out using 1-2 service operation vessels (SOV) and 1-2 crew transfer vessels (CTV). The main activities will be SOV and CTV transport to and from the selected ports, as well as movements within the Thor OWF site. The SOV will re-supply via the Port of Esbjerg on a regular basis, while the CTVs will move between the Thor OWF site and the Port of Thorsminde, where the construction base will be located.

Commissioning activities will comprise the testing of individual wind turbine connections to the transformer platform as well as the high-voltage system connection and switching operations. The use of portable generators for commissioning works prior to turbine energisation is expected, however, the extent of this will vary depending on the progress of other works e.g. grid energisation, array cable integrity etc.

Handover to the operating team will occur when all commissioning operations are complete and the turbines perform according to agreed criteria set out in the Turbine Supply Agreement. It is expected that the commissioning of the wind turbines will take place concurrently with the installation works and have a duration of 9-10 months, assuming that 96 hours is required for the commissioning of a single turbine.

4.9 Airborne noise from turbine operation

There are two types of noise associated with operation of wind turbines: aerodynamic and mechanical noise.

Aerodynamic noise is broad band in nature, relatively unobtrusive and is strongly influenced by incident conditions, wind speed and turbulence intensity. An operational sound power level measured at a height of 10 m above ground level is expected in the order of 108 dB(A) to 122.1 dB(A), depending on the selected turbine type and the wind speed (between 6–8 m/s).

Mechanical noise is generated by components inside the turbine nacelle and can be radiated by the shell of the nacelle, blades and the tower structure.

5. Wind turbine foundations

The turbines will be supported by monopile foundations fixed to the seabed, comprising hollow steel piles driven into the seabed upon which the tower is attached (as illustrated in Figure 4.1).

5.1 Description

Monopile foundations comprise a single hollow steel pile driven into the seabed upon which the wind turbine tower is mounted and bolted. The monopile foundation will be installed via piling into the seabed to depths of between 20–50 m, depending on the specific location for each monopile.

There will be no transition piece between the foundation and wind turbine tower. Instead, the wind turbine tower will be lifted directly onto the monopile at each foundation site offshore and attached to the monopile using a bolted connection. The internal platform, external platform and boat landing will all be fabricated onshore before being transported offshore, lifted into place and connected to the monopile. The internal platform cassette will be fabricated of steel onshore and will be lifted offshore onto an internal landing ring within the monopile. The boat landing will be fabricated of steel and connected to the monopile offshore using pin-bucket connections. The external platform will be constructed of either steel or reinforced concrete and will be connected to the monopile offshore using a bolted or grouted connection.

5.1.1 Scour protection

Scour is the term used for the localized removal of sediment from the area around the base of support structures located in moving water. If the seabed is erodible and the flow is sufficiently high, a scour hole forms around the structure. There are two different ways to address scour; either to allow for scour in the design of the foundation (thereby assuming a corresponding larger water depth at the foundation), or to install scour protection around the structure, for example using fronded mattresses or via rock installation.

For Thor OWF, scour protection is expected to be installed around monopile foundations. The scour protection will likely consist of a lower filter layer comprising stones averaging 5–10 cm in diameter and an upper armour layer comprising rocks between 10–50 cm in diameter. Depending on the hydrodynamic environment, filter layers will be approximately 0.8 m in thickness and have a bottom diameter of up to 45 m. The overlying armour layer will have an approximate thickness of 1–2 m and have a bottom diameter of up to approximately 36 m. Typical scour protection for a monopile foundation is shown in Figure 5.1.

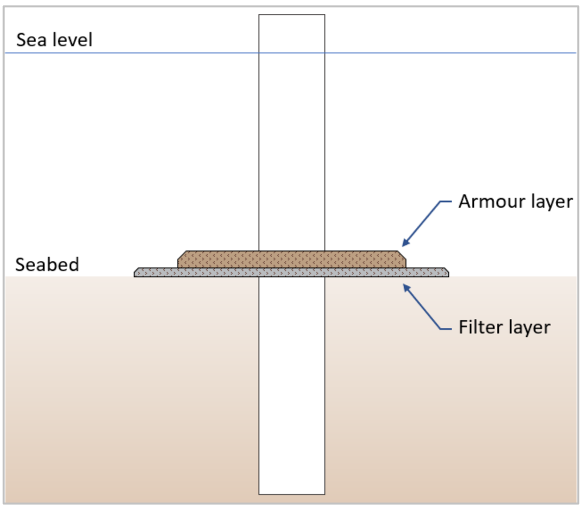

Figure 5.1: Example of typical scour protection around a monopile foundation. The bottom filter layer comprises smaller rocks and has a larger diameter compared to the top amour layer.

5.2 Dimensions

The dimensions of monopile foundations are specific to the exact location of installation and are therefore dependent on local bathymetry and seabed conditions. However, estimated values for the dimensions, weight, required ground penetration and scour protection footprint required for the monopile foundation at Thor OWF are summarised in Table 5.1.

Table 5.1: Key dimensions, footprint and volume of scour protection needed for monopile foundations at Thor OWF.

Foundation	Dimensions
Pile diameter at seabed (m)	8.0–10.0
Number of piles per turbine foundation	1
Pile length (m)	65–105
Ground penetration (below mud line) (m)	20–50
Footprint area per monopile (m^2)	50–78,5
Total weight per foundation (t)	1,100–1,800
Scour protection	
Scour footprint area per foundation (m^2)	1,550
Scour volume per foundation (m^3)	2,210–3,180

5.3 Materials

The type and weight of raw materials used for monopile foundations are listed in Table 5.2. The primary materials used are steel, grouting and rocks.

Table 5.2: Summary of the type, total weight and origin of raw materials required per monopile foundation.

Component	Material type	Origin of material	Weight (metric ton per foundation)
Monopile	Steel	Worldwide	1,100–1,800
	Grouting	Europe	4
Secondary structures (e.g. external platform, ladders)	Steel	Worldwide	100
External platform	Concrete	Europe	150
Scour protection	Rock (normal and high density for filter and armour layer respectively)	Europe (Norway)	4,600

5.3.1 Corrosion protection

The monopile foundations will be protected against corrosion using an Impressed Current Cathodic Protection (ICCP) system placed on the subsea structures. ICCP is a standard corrosion protection system comprising Mixed Metal Oxide (MMO) coated titanium anodes which are connected to an external power source, which provides a current leading to the electrochemical reaction required for cathodic protection to occur. The anodes are standard products for offshore structures and the number and size of anodes will be determined during the detailed design.

Furthermore, protective coating will be applied to the foundations, including coating systems, thermal spray metallization and galvanization. An example coating concept is detailed in Table 5.3. The use of substances in relation to the protective coating will comply with the Chemicals Act by the Danish EPA (LBK nr 6 af 04/01/2023).

Table 5.3: Indicative coating concept for corrosion protection.

Monopile sub-structure	Exposure zone	Coating
Primary steel-work — external	Atmospheric zone	Epoxy (base case) or Epoxy Glass Flake (option) / polyurethane coating system to CX and durability category VH (very high). MDFT 400µm or greater if required to meet the required categories. Finish coat two-pack polyurethane or acrylic urethane.
	Splash zone	Epoxy (option) or Epoxy Glass Flake (base case) coating system to CX/Im4 and durability category VH (very high). MDFT 600µm or greater if required to meet the required categories. For long-term UV protection, polyurethane topcoat shall be used for epoxy-based systems.
	Submerged scour and permanently buried zones	Protection by cathodic protection (CP) with option for coating to reduce load on CP system. Coating system if applied: Minimum two coats of Epoxy (option) or Epoxy Glass Flake (base base) coating system to Im4 (high), MDFT 350 µm.
Primary steel-work — internal	Internal atmospheric zone above airtight platform	Epoxy coating system better than C4 (high), MDFT 320 µm.
	Internal atmospheric zone below airtight platform	Epoxy (base case) multilayer coating system with a MDFT 600 µm.
	Submerged scour and permanently buried zones	Corrosion control via coating and cathodic protection or corrosion allowance. Epoxy (base case) or Epoxy Glass Flake (option) coating system to Im4/Im3 and durability category V (high). MDFT 350µm or greater if required to meet the required categories. Coating to be resistant to cathodic disbondment.

5.4 Colour and marking

The foundations for each wind turbine will be painted yellow, as stipulated in Annex 3.2.1 of the Concession Agreement, from the MSL up to a height of minimum 15 meters (relative to HAT), or up to the height of the navigational markings if positioned higher than 15 meters. The colour RAL 1023 (traffic yellow) is recommended (IALA, 2021).

Reflective identification consisting of numbering/lettering must be placed on each wind turbine structure, either on the tower, directly onto the foundation or on the access platform using a sign or panel. The numbers/letters must be 0.5–1 m in size and must consist of black letters on a yellow background. The specific proposal must be approved by the Danish Maritime Authority.

5.5 Installation of foundations

5.5.1 Seabed preparation

The installation of monopile foundations is not expected to require significant seabed preparation works. However, the removal of obstructions such as large rocks and boulders may be necessary in some instances. Where boulder clearance is needed, a typical boulder grab system will be used, and the boulders will be relocated to a local or adjacent position. The relocation of rocks will lead to a permanent change in the seabed, whereby rocks with a diameter of approximately 0.5-3.0 m will be moved leading to local changes in the seabed. Approximately 300 boulders in total are expected to be relocated during the construction phase for the entire offshore wind farm.

Scour protection filter layers will be installed prior to piling. After piling is complete, the second armour layer of scour protection is typically installed. Scour protection consists of rock placement, whereby rocks are graded and loaded onto a suitable vessel at a port prior to transportation. Once at the site, scour protection will be deployed from the host vessel(s), either directly onto the seabed from a barge or using a bucket grab or telescopic tube.

5.5.2 Installation of monopile foundations

The monopiles will be transported by barge to Thor OWF, either directly from the manufacturer or from another load-out port. Once in position, the installation of monopile foundations will take place from either a jack-up platform or floating vessel equipped with 1-2 mounted marine cranes, a piling frame and pile tilting equipment. Piling will be carried out by ramming the piles into the seabed. The hammer type and size, the blow strength and frequency, and the total number of blows needed per pile varies depending on the seabed and subsurface conditions. The technical specifications for monopile installation for Thor OWF are listed in Table 5.4. A small drilling spread may also be required if hard substrates are encountered during piling, however this is not expected within Thor OWF. An additional jack-up vessel, support vessel, tug, safety vessel and CTV may also be used. A top cover will be added to the top of the monopile foundation after installation of the secondary steel until the wind turbines are installed.

Table 5.4: Technical specifications for monopile installation.

Installation details for piling	
Blow strength (kJ)	5,000
Total number of blows per pile	5,000-20,000
Blow frequency (blows/min)	30-70

Piling will be initiated using a soft start/ramp-up procedure, whereby the force and frequency of pile strikes increases over a predetermined amount of time, as piling cannot be initiated using full hammer force (technical constraint). The procedure will vary depending on the location, size of monopile, hammer energy, number of pile strikes and the strike frequency.

It is expected that one monopile will be installed per day, however conditions may arise during the construction work which necessitate the installation of two monopiles per day, whereby the installation of the second monopile will begin as soon as the first installation is finished.

5.5.3 Installation time schedule

The installation of foundations will be completed over a period of approximately 8–9 months, excluding weather down-time. The total estimated timeframe for the key installation activities is shown below.

Scour installation:	160 days
Piling:	72 days
Installation of platform:	79 days

All timeframes are based on a P50 schedule, which represents the most likely scenario.

6. Offshore substation

An offshore substation platform will be installed within the eastern part of Thor OWF close to the export cable corridor. The planned location of the offshore substation is shown in Figure 6.1.

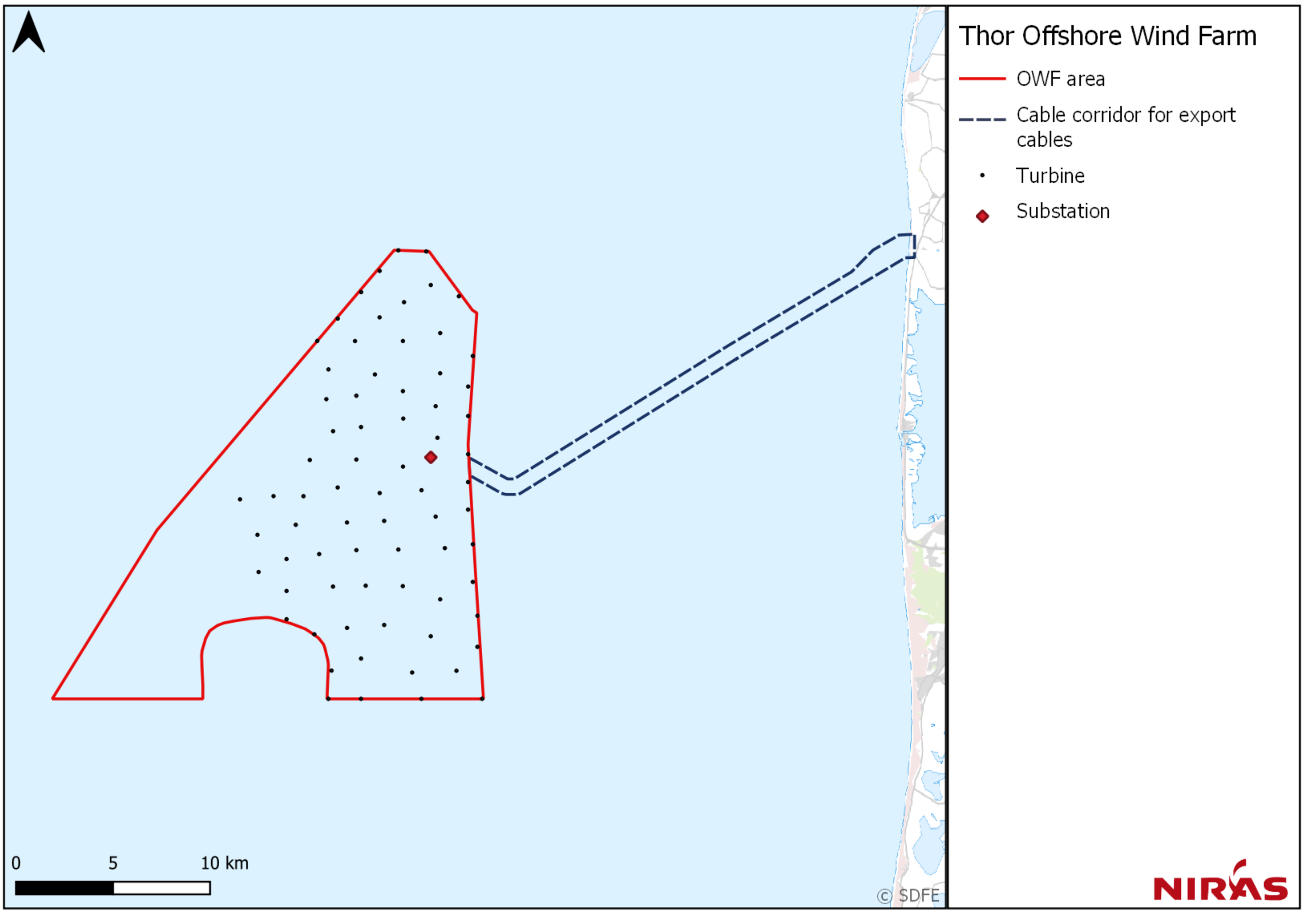

Figure 6.1: Location of the offshore substation platform in Thor OWF which will gather electricity from the turbines.

6.1 Description

The offshore substation consists of a topside and foundation structure. The primary function of the substation is to collect, stabilise and transform electricity generated from the wind turbines into a higher voltage in order to reduce electrical losses prior to exporting the power to land via export cables.

Inter-array cables from the wind turbine arrays will be routed through J-tubes on the offshore substation jacket foundation and onto the substation's cable deck. The inter-array cables will then be routed via switchgear to two 275/66kV transformers, housed on the main equipment deck along with switchrooms and earthing transformers, where the electricity is transformed. The 275/66kV transformers will be connected via switchgear to two export cables also routed via J-tubes and pulled onto the cable deck, which connect to the onshore transmission network via the cable corridor outlined in Figure 6.1. The substation's topside will also house key operational facilities (e.g. control room, welfare facilities suitable for a normally unmanned platform), as well as critical systems such as navigation and aviation light control, fire suppression, rainwater separation and communication antennas.

Although operated remotely, the substation will be designed to accommodate a normal working team of 4–6 persons and will therefore be equipped with a heli-hoist platform, two boat landings and two pairs of access points for motion compensated gangways. The substation will be able to accommodate up to 12 persons in case of bad weather.

In case of unplanned disconnection from the onshore transmission network, diesel-powered back-up generators, or battery/UPS, will be available to power essential services on the substation platform. In the case of diesel-powered generators, the substation will be installed with containers for collecting oil as well as diesel spillages in the event of leakages. The foundation used for the offshore substation will be a post-piled jacket (Figure 6.2) with J-tubes equipped with messenger wires.

Figure 6.2: Typical offshore substation platform with post-piled jacket foundation.

6.2 Dimensions

6.2.1 Substation platform

The dimensions of the substation platform are summarised in Table 6.1.

Table 6.1: Dimensions of the substation platform at Thor OWF.

Parameter	
Max. platform length (m)	45.0
Max. platform width (m)	40.0
Max. platform height (m) above MSL*	60.0
Min. platform height (m) above MSL*	35

**Measured from Mean Sea Level to the highest point.*

6.2.2 Foundation

The dimensions of the jacket foundation supporting the substation platform will depend on the specific seabed conditions and water depth (averaging between 26–30 meters) at the chosen substation location inside the perimeter of the windfarm. The approximate dimensions of the substation jacket foundation are summarised in Table 6.2 and are based on the location outlined in Figure 6.1.

Table 6.2: Dimensions of the post-piled jacket foundation of the substation platform at Thor OWF.

Parameter	
Pile diameter at seabed (m)	2.5
Number of piles	4
Pile length (m)	85
Ground penetration (below mud line) (m)	60
Footprint area of jacket leg (x4) (m^2)	288

6.3 Materials

The type and weight of primary raw materials used in the substation, including the foundation, are summarised in Table 6.3, while the estimated quantities of oils and fluids used in the topside substation are listed in Table 6.4.

Table 6.3: Summary of the type and weight of materials required for the offshore substation platform and jacket foundation. The estimated weights of materials for transformers are based on the percentages given in (Hegedic, Opetuk, Dukic, & Draskovic, 2016).

	Material type	**Weight (metric ton)**
Substation		
Structural frame	Steel	1,250
Transformers (2 pcs)	Iron	290
	Steel	150
	Copper	115
Cables (LV/HV)	Aluminium	8–10
	Copper	4–6
	Steel	40–45
	PE	14–18
Foundation		
Jacket (excl. pin piles)	Steel	2,400
Pin piles (x4)	Steel	1,410

Table 6.4: Estimated quantities of oils and fluids used in the offshore substation platform.

Component	**Type**	**Estimated amount (kg)**
Switchgear	Oil	400
Diesel generator	Oil	10,000
Transformers (2 pcs)	Oil	140,000

6.3.1 Corrosion protection

The corrotion protection for the offshore substation will be of the same type used for the wind turbine foundations (described in section 5.3.1).

6.4 Colour

There are no specific requirements for the colour of offshore substation platforms. However, it is recommended that the topside be painted using the same light grey colour (RAL 7035) as the turbines. The lower section of the offshore substation, from MSL and up to a height of 15 meters (relative to HAT), or up to the height of the navigation mark if positioned higher than 15 meters, will be painted yellow, as described in Annex 3.2.1 of the Concession Agreement. The colour RAL 1023 (traffic yellow) is recommended (IALA, 2021).

6.5 Lighting and marking

As the offshore substation will be situated inside the wind farm perimeter and has a total height of less than 100 m, there are no specific requirements regarding permanent lighting (BL 3-11 2. udgave af 28/04/2014, 2014). Temporary work area markings will, however, be deployed around the entire OWF prior to, and throughout the duration of, construction works, thereby ensuring the safety of maritime navigation (see section 9.1 and section 9.2).

The offshore substation must also be fitted with reflective identification panels displaying numbers/letters, which must be 0.5–1 m in size. It is recommended that black letters on a yellow background are used. The specific proposal must be approved by the Danish Maritime Authority.

6.6 Installation

The installation of the post-piled jacket foundation and the substation topside will likely be conducted in a split campaign, although the fabrication and installation timelines for the Thor OWF may dictate that sequential installation operations are necessary.

6.6.1 Seabed preparation

Seabed preparation for the substation will include activities such as relocating boulders from the site. The relocation of boulders will likely be conducted using a boulder grab, with boulders moved to local positions adjacent to the jacket legs. The relocation of rocks will lead to a permanent change in the seabed, whereby rocks with a diameter of approximately 0.5-3.0 m will be moved leading to local changes in the seabed. Approximately 300 boulders in total are expected to be relocated during the construction phase for the entire offshore wind farm.

6.6.2 Jacket foundation

A 4-legged post-piled jacket foundation will be used for the offshore substation. The jacket foundation will be transported to Thor OWF using towed barges, where it will be lifted and lowered onto the seabed via a heavy lift vessel (HLV).

Piles will subsequently be driven through guides in the jacket legs using an impact hammer, with the hammer size, blow strength and frequency as well as the total number of blows dependent on the seabed and subsurface conditions. The requirements for the piling activities associated with securing the jacket foundation to the seabed are shown in Table 6.5.

Table 6.5: Technical specifications for substation foundation installation.

Jacket pin pile installation	
Blow strength (kJ)	800-1,200
Total number of blows per pile	6,800
Blow frequency (blows/min)	60
Number of piles installed per 24h	2

The jacket will be levelled to meet the required tolerance prior to the permanent connection between piles and jacket being established. The permanent connection is formed by grouting the space (grout annulus) between the piles and the pile sleeve of the jacket. Levelling may be conducted by means of hydraulic tools and grippers and be augmented by simple means such as cutting off excess material at the top of relevant jacket legs to the appropriate level.

The grouted connection will be established by mixing the grout on the HLV and subsequently pumping the grout into the grout annulus. Pumping of the grout will be performed using either fixed lines on the jacket or flexible hosing deployed by remotely operation vehicle (ROV). Grout seals will prevent grout escaping through the bottom of the grout annulus and into the seabed.

6.6.3 Substation platform

The HLV will lift the topside from the towed transportation barge and set it down onto the jacket foundation. Lastly, the substation topside will be welded to the jacket. The installation of the substation will be assisted by multiple support vessels, for example tugs, barges, anchor handlers, platform supply vessels, jack-up barge, SOVs or other offshore construction vessels.

6.6.4 Installation schedule

The installation of the offshore substation platform and jacket foundation will be completed over a period of approximately 5 months, including jacket and topside installation and commissioning. The total estimated timeframe for the key offshore installation activities is shown below.

Jacket offshore installation:	10 days
Topside offshore installation:	10 days
Topside and jacket interface:	12 days
Commissioning:	87 days

All timeframes are based on a P50 schedule, which represents the most likely scenario.

7. Inter-array cables

7.1 Description

Medium voltage (66 kV) alternating current (AC) inter-array cables will connect each of the 14 MW wind turbines via a series of 16 array strings, which will then be connected to an offshore substation platform. An indicative layout for the inter-array cables is shown in Figure 7.1. The inter-array cables will be routed toward the substation, through J-tubes and onto the substation platform. Here they will connect to two 275/66 kV transformers and onward to two 275 kV export cables.

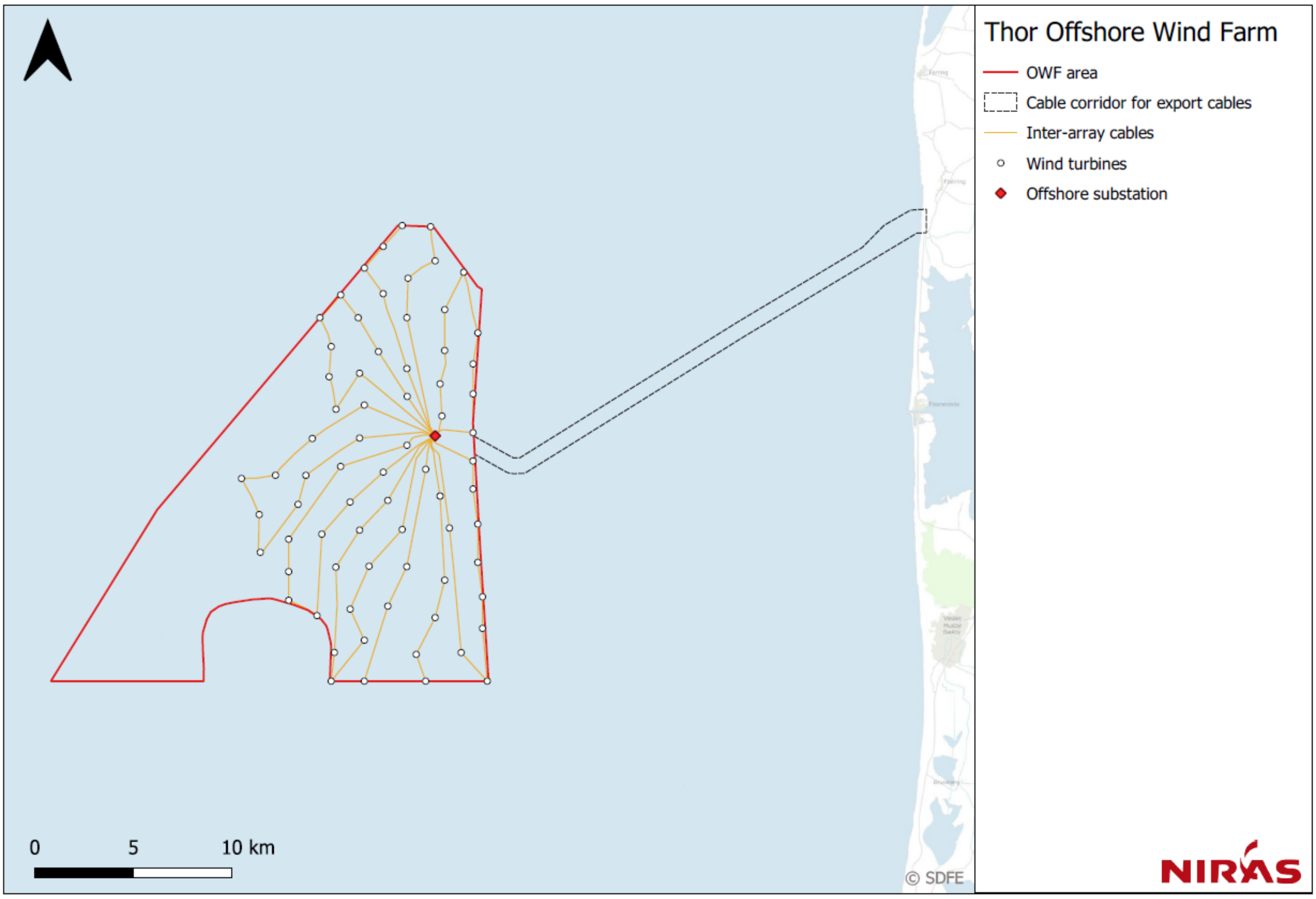

Figure 7.1: Indicative layout for inter-array cables connecting the wind turbines with the offshore substation.

The inter-array cables will contain three aluminium conductors encased within a steel armour layer and an outer covering comprising polyethylene (PE), possibly with a radial water barrier of lead underneath. The three cores will each be surrounded by cross-linked polyethylene (XLPE) insulation. Additionally, inter-array cables will have an integrated optical fibre cable with 48 fibres for communication with the control system in each wind turbine (a part of the SCADA system for the wind farm).

7.2 Dimensions

The technical specifications and dimensions of the inter-array cables are summarised in Table 7.1. Each core will have a cross-section of between 240–1,000 mm^2, depending on proximity of the cable to the offshore substation platform. The inter-array cable size is determined by the ampacity requirements of the particular cable; those closest to the substation and with the highest number for associated turbines will be the largest, while those furthest away from the substation with fewer number of associated turbines will be the smallest. The current layout assumes 60 km of 1,000 mm^2, 125 km of 500 mm^2 and 20 km of 240 mm^2 cables. Consequently, the inter-array cables will have an average weight (in air) in the range of 20–50 kg/m.

Table 7.1: Specifications and dimensions for the 66 kV inter-array cables to be used for Thor OWF.

Parameter	
Array strings	16
Conductor cross section (mm^2)	240–1,000
Material (conductor)	Aluminium
Diameter (mm)	120–195
Weight (kg/m)	20–50
Total length* (km)	205

** total length represents the combined estimated length for 72 wind turbines.*

7.3 Materials

The main type and estimated weight of materials in the expected inter-array cables are shown in Table 7.2. The primary materials used are aluminium for the core, steel for armouring, aluminium/copper wiring, and PE for insulation. Depending on the local seabed conditions, rock berms and/or concrete mattresses may be used to protect the cables. Oil-free cables will be used for all inter-array cables to prevent any risk of leakage and pollution.

Table 7.2: Summary of the type and weight of raw materials in 66 kV inter-array cables. The weight is specified for material used per meter of cable. Final weights may vary by ± 5 %.

Cable design	Material type	Weight (approx. kg/m)
3-core 240 mm^2 cable	Aluminium	1.8–2.1
	Copper	0.5–0.8
	Steel	13–14
	PE	4.8–5.0
3-core 500 mm^2 cable	Aluminium	2.6–4.0
	Copper	0.5–0.8
	Steel	15–16
	PE	5.0–5.7
3-core 1000 mm^2 cable	Aluminium	8.0–9.0
	Copper	0.5–1.1
	Steel	19–24
	PE	7.0–8.2

7.4 Installation

Inter-array cables will be placed on turntables on a cable-laying vessel (CLV) or flat top pontoon or anchor barge at a load-out port prior to transportation to the Thor OWF site. The Port of Thorsminde is planned for use by CTVs. The inter-array cables will be installed on the seabed using a purpose built CLV and an installation support vessel (ISV).

7.4.1 Seabed preparation

A number of activities will be carried out prior to the cable laying. Route clearance will be carried out using a pre-lay grapnel run (PLGR) and boulder relocation. The grapnel run involves pulling a grapnel train along the seabed in order to hook and remove debris (e.g. old wires or fishing nets). Boulders will be collected using a boulder grab system. Boulders will be relocated locally outside of the planned cable route (but inside the Thor OWF project area). The grapnel run and boulder relocation will be carried out using a trenching support vessel (TSV), ISV or similar. The relocation of rocks will lead to a permanent change in the seabed, whereby rocks with a diameter of approximately 0.5-3.0 m will be moved leading to local changes in the seabed. Approximately 300 boulders in total are expected to be relocated during the construction phase for the entire offshore wind farm.

7.4.2 Cable laying

The CLV will approach the first wind turbine and secure its position using the vessel dynamic positioning system (DP). Once in position, the CLV will lower the first end of the cable from the turntable onto the seabed, after which the cable will be pulled through the cable protection system (CPS) and up through the J-tube or monopile entry hole, from where it will be secured on the hang-off on the turbine foundation.

The CLV will then travel to the next wind turbine foundation while continuously laying the cable onto the seabed. Upon reaching the second location, the cable will be cut to the required length and the second cable end will then be lowered to the seabed using a sub-sea quadrant. The cable will again be pulled through the CPS, up through the J-tube or monopile entry hole and secured on the hang-off on the turbine foundation. An ISV and CTVs may assist the CLV by deploying personnel and equipment to conduct preparatory and completion tasks on the foundations.

Inter-array cables approaching the substation platform will be lowered onto the seabed for later burial.

7.4.3 Post-lay activities

After laying the cable onto the seabed, additional operations are expected to ensure the inter-array cables are protected.

Cable protection is expected via burial using a ROV equipped with a jetting tool and mechanical cutter. Jetting uses high-powered water pumps feeding purpose-built jet-legs, which liquefy the seabed on either side of the cable, while mechanical cutting uses a cutting head to loosen the sediment directly below the cable. During jetting, the ROV will move forward and lower the cable into a trench. The cable will be buried to a target burial depth of approximately 1.5 m below stable seabed. The width of the seabed affected by the jetting operation depends on the seabed conditions and is approximately 1 m in clay and 2 m in sandy sediment.

The last 75 m of each inter-array cable string approaching the offshore substation will be buried into the seabed using controlled flow excavation (CFE). CFE uses a specialised ROV and work by creating a pressurised water column which displaces sediment on the seabed, creating a trench into which the export cable can be lowered. Burial activities are expected to progress at a rate of 50–350 m/hour.

Depending on the specific seabed conditions, inter-array cables may be left unburied and may therefore require protection by installing loose rock (rock berm) and/or concrete mattresses from a rock placement vessel. If used, rock sizes will typically range from 10–40 cm. For example, rock protection is expected to be required in the vicinity around the turbine foundations in order to stabilise the cables entering/exiting from the monopile and to prevent scouring from compromising their stability. The length of inter-array cable within Thor OWF that may potentially require remedial protection via loose rock and/or concrete mattresses is estimated at up to 20 % of the total cable route. Protection using stones or concrete mattresses will have an average width of approximately 2 m.

The total area of seabed temporarily disturbed during the installation of inter-array cables will be approximately 343,000 m^2, while the area permanently disturbed from cable protection will be 82,000 m^2 (Table 7.3).

Table 7.3: Area of seabed temporarily and permanently disturbed from the installation and protection of inter-array cables.

Method	Sediment type	Seabed width disturbed (m)	Length (m)	Area (m^2)
Temporary				
Mechanical cutting	Clay/stone	1	77,000	77,000
Jetting	Sand	2	128,000	256,000
CFE	Sand/Clay	8.5	1,200	10,200
Permanent				
Cable protection	-	2	41,000	82,000

7.4.4 Installation time schedule

The installation of inter-array cables will be completed over a period of approximately 5 months, excluding weather down-time. The total estimated timeframe for the key installation activities is shown below:

Seabed preparation: 40 days
Cable laying: 100 days
Cable burial: 130 days

All timeframes are based on a P50 schedule, which represents the most likely scenario.

8. Export cables

8.1 Description

The offshore substation platform will be connected to a transition joint bay on land via two high voltage (275 kV) alternating current (AC) submarine export cables, through which the transformed electricity from the turbines will be carried to land. The export cables will be installed broadly parallel to one another within the cable corridor, with the cables separated by approximately 25–100 m (Figure 8.1). The total length of each of the two export cables is approximately 30 km.

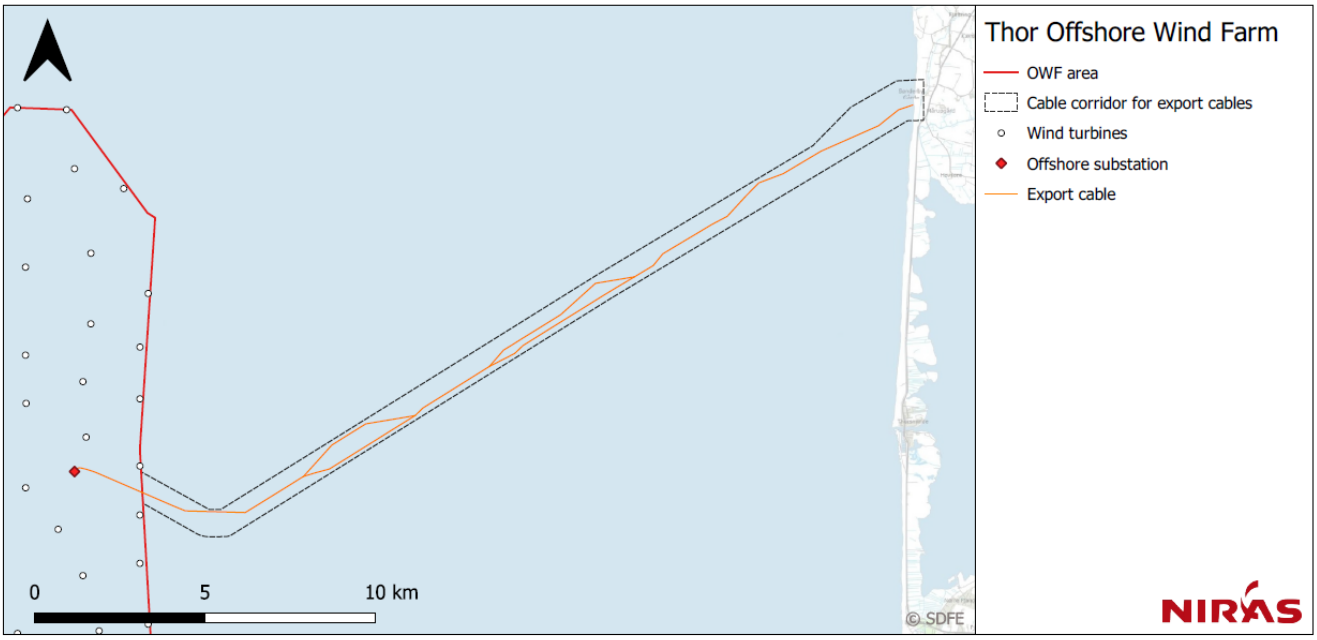

Figure 8.1: Indicative export cable route within the cable corridor for Thor OWF. The areas of divergences represent a possible alternative routing for both cables.

The export cables will contain three cores comprising either aluminium or copper conductors, each encased within XLPE insulation and lead sheathing. The three cores will be surrounded by a galvanised steel, polymeric armour wires and/or stainless steel armouring covered by an outer protective bitumen sheath and yarn rovings (Figure 8.2). Each export cable will contain two tubes containing integrated optical fibres for communication and for temperature measurement.

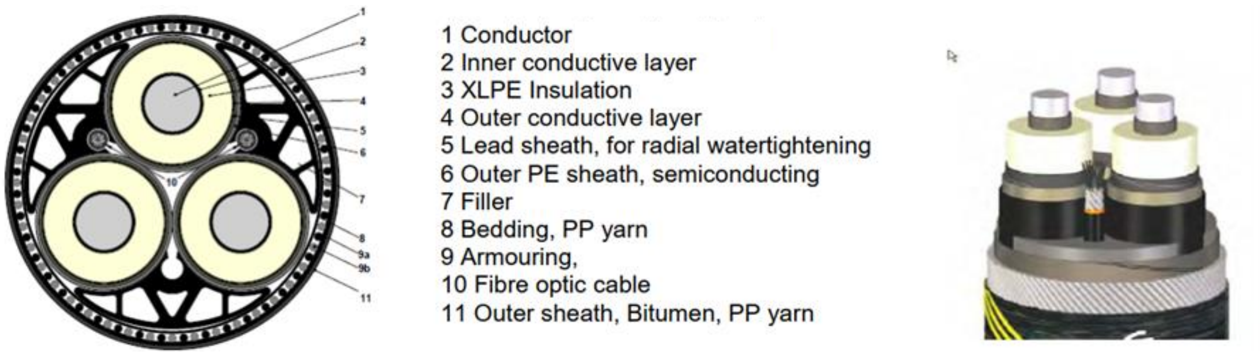

Figure 8.2: Illustation of typical offshore electrical export cables with three conductors, armouring and a protective outer sheath.

8.2 Dimensions

The specifications and dimensions of the two different types of high voltage 275 kV export cable expected to be used for Thor OWF are shown in Table 8.1. The export cabling will contain copper cores from the transition joint connecting it to the onshore cable, located behind the dunes, to a distance of approximately 2-4 km offshore, while the cabling will contain aluminium cores further out to the substation platform. The cables will be pre-joined during the cable manufacturing.

Table 8.1: Specifications and dimensions of the different types of offshore export cables considered for Thor OWF.

Conductor material	Core cross-section (mm^2)*	Weight in air (kg/m)*	Diameter (mm)*	Armouring material(s)	Length of cable required (km)
Aluminium	1900	100	282	Galvanised, polymer and/or stainless steel wires	26-28 (2x)
Copper	2500	183	305	Galvanised, polymer and/or stainless steel wires	2-4 (2x)

** Final specification may vary by ± 25 %.*

8.3 Materials

The main type and weights for the raw materials used in the 275 kV export cables are summarised in Table 8.2. The primary materials comprise aluminium or copper conductors, XLPE insulation, steel/polymeric armouring and an outer protective coating made of bitumen and polypropylene. Oil-free cables will be used for the export cables to prevent any risk of leakage and pollution.

Table 8.2: Summary of the type and weight of raw materials for the 275 kV export cables. The weight is specified for the amount of material used per meter of cable.

Cable design	Material type	Weight (approx. kg/m)*
3-core Aluminium 1900 mm^2 cable	Aluminium	17
	Steel	34
	PE/PP	23
	Lead	26
3-core copper 2500 mm^2 cable	Copper	70
	Steel	41
	PE/PP	42
	Lead	30

** Final specification may vary by ± 25 %.*

8.4 Installation

Export cables are expected to be placed on turntables on a CLV at the load-out port before being transported to the cable corridor for Thor OWF, with the Port of Thorsminde expected to be used for CTVs. Each export cable will be installed as a single jointless cable.

The offshore installation cycle comprises seabed preparation, cable laying and post-lay activities, with installation occurring via one of two possible scenarios, depending on the nature of the mobile sediments present within the nearshore area. Scenario 1 describes installation of the export cables using a combination of dredging, jetting, mechanical cutting and CFE, while scenario 2 describes installation via jetting, mechanical cutting and CFE only. For both scenarios, the use of rock placement and/or concrete mattresses) may be necessary under certain conditions.

The sediment in the cable corridor consists primarily of sand, stones and mixed substrate (MTT, 2020b), and the seabed is characterised by large sand waves, indicating highly mobile sediments with a dominant direction of transport from north to south (DHI, 2020). The presence and nature of any mobile sand layer in the cable corridor therefore depends on how sand waves migrate through the area.

In a study of the seabed morphology of the gross project area and cable corridor (MarineSpace Ltd, 2022a), migrating sand waves were observed moving at a velocity of less than 10 m to 15.5 m/year. The study concludes that the migrating sand waves can result in seabed changes of 1.2 to 1.75 m over a relatively short period of time. The chosen installation scenario will depend on the nature of mobile sediments within the cable corridor at the time of installation, although scenario 2 is the preferred method.

8.4.1 Scenario 1: Cable burial with dredging

8.4.1.1 Seabed preparation

A number of activities will be carried out prior to cable laying. Route clearance will be carried out using a pre-lay grapnel run and boulder relocation. The grapnel run involves pulling a grapnel train along the seabed in order to hook and remove debris (e.g. old wires or fishing nets).

Boulders will be collected using a boulder grab system. Boulders will be relocated locally outside of the planned cable route (but inside the cable corridor). The grapnel run and boulder relocation will be carried out using a trenching support vessel (TSV), ISV or similar. The relocation of rocks will lead to a permanent change in the seabed, whereby rocks with a diameter of approximately 0.5-3.0 m will be moved leading to local changes in the seabed. Approximately 300 boulders in total are expected to be relocated during the construction phase for the entire offshore wind farm.

The seabed in the nearshore area of the planned export cable routes, between the coastline and out to approximately 3 km offshore, is characterised by mobile sediment and a sand bank. In scenario 1, the sandbank and the mobile sediment present along the cable routes will be dredged prior to cable laying and burial using a combination of a Backhoe Dredger and a TSHD. The purpose of dredging is to reach stable seabed to create a surface suitable for the different cable burial ROV's to operate in.

The seabed conditions within the nearshore area, from the coastline and out to approximately 3 km, is shown in Figure 8.3.

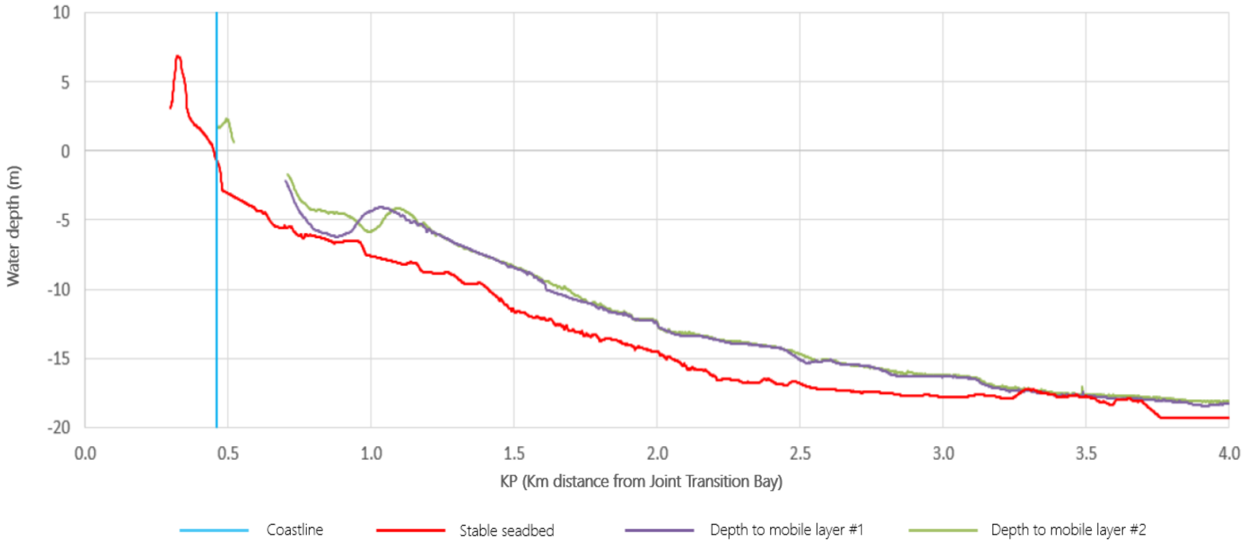

Figure 8.3: Transect of the nearshore area of the cable corridor showing stable seabed (red line) and the top of the mobile sediment layer (green and purple lines), based on two geophysical surveys. The coastline is located approximately at KP 0.46 (blue line). Illustration from Jan De Nul.

A Backhoe Dredger (Figure 8.4) will be used to remove mobile sediment and an approximately 2 m thick sandbank from the planned export cable routes in an area between the coastline and out to approximately 550 m offshore. Sediment will be placed adjacent to the respective cable routes, so that the excavated trenches can naturally back-fill once the cables have been lain.

Figure 8.4: Illustration of a backhoe dredger excavating a trench in a nearshore setting. The excavated sediment is moved to one side of the cable trench to allow for natural backfilling. Illustration from Jan De Nul.

Next, a TSHD will be deployed along the planned cable routes from approximately 550–2,850 m offshore. The TSHD is a standard dredging vessel which utilises a suction pipe attached to a draghead placed on the seabed. The draghead is aided by a water jet system which liquefies a sand layer by mixing it with water, after which the sand and water mix is drawn up through the suction pipe using a centrifugal pump. The TSHD will remove an area of mobile sediment up to 2–3 m thick. The sediment dredged using the TSHD will be deposited (bypassed) onto the seabed approximately

500–1,000 m to the north of the planned cable routes at 15 m water depth, in an area with a sandy seabed (bypass area) located within the original pre-investigation area for export cables (Figure 8.5).

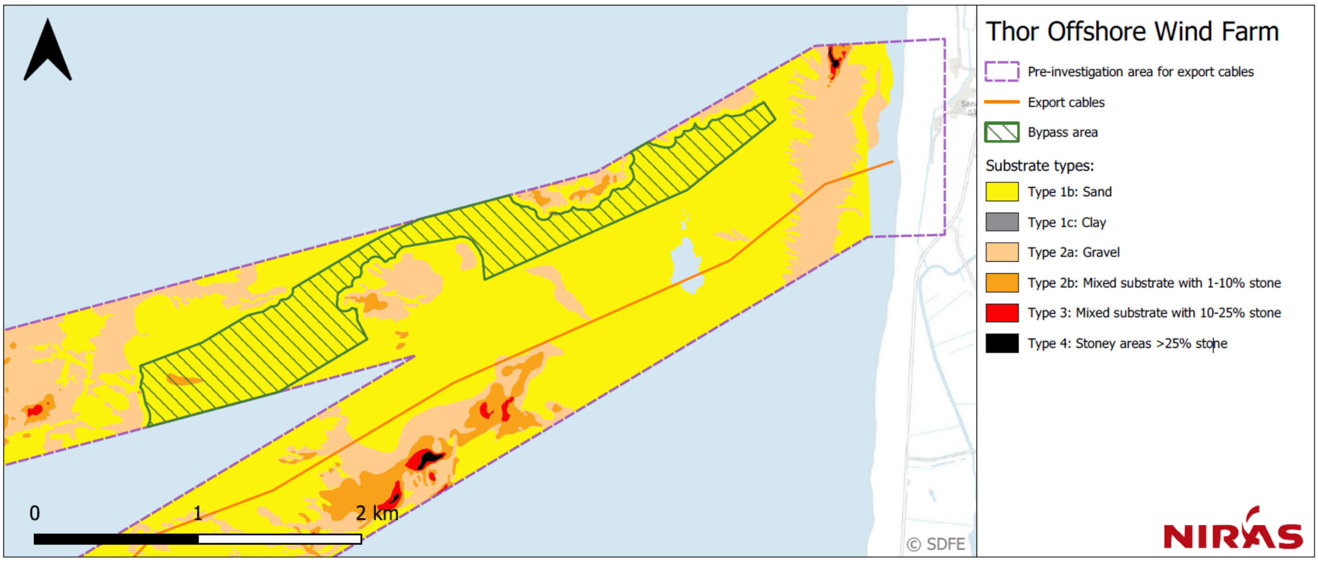

Figure 8.5: Map highlighting the bypass area (green dashed box) approximately 500–1,000 m north of the planned export cable routes. The primary sediment type located within the pre-investigation area for export cables is sand. An indicative export cable route is shown in the map.

Once deposited (bypassed), the dredged sediment is expected to naturally backfill the area excavated over the planned cable routes due to the high sediment mobility documented in the area and described in studies on seabed mobility (MarineSpace Ltd, 2022b; MarineSpace Ltd, 2022a). This process will be monitored via surveying to ensure that natural backfilling occurs as expected. If necessary, the dredged material will be recovered and used to reestablish the cable corridor following cable burial (see section 8.4.1.3) The projected volumes of sediment to be removed during seabed preparation will depend on the bottom width required for the different post-lay cable burial methods, which range from 6.5–22.5 m in width.

Table 8.3 summarises the different methods and associated indicative lengths which need to be dredged, the bottom width of the dredged area needed for the different cable burial equipment, and the projected volumes of sediment to be removed in scenario 1 during seabed preparation.

Table 8.3: Summary of methods and estimated dredged and pre-trenched sediment volumes during seabed preparation for the two export cable routes. The area of seabed disturbed during seabed preparation is also shown.

Section (m)	Method	Bottom width (m)	Sediment volume (m^3)*	Area of seabed disturbed (m^2)*
Approx. 0-550	Backhoe Dredger	22.5	Up to 40,000	Up to 40.000
Approx. 550–2,850	Trailing Suction Hopper Dredger	Up to 22.5	Up to 300,000	Up to 160.000

** Assumes a slope ratio of 1:3.*

8.4.1.2 Cable laying

Following dredging, the CLV will begin the cable laying procedure by approaching the shoreline, from where the first export cable will be floated in toward landfall from the vessels turntable. Several smaller guidance vessels will be used to ensure the floats remain in position as the cable approaches landfall, after which it will pass onto pre-installed rollers on the beach prior to being pulled into the transition joint bay. The CLV will then proceed within the defined cable corridor toward the offshore substation platform, continuously laying export cable onto the seabed. The second cable end will be cut to the required length and lowered to the seabed. The cable will then be pulled through the CPS and up through the J-tube, where it will be secured on the hang-off on the substation cable deck on the offshore substation. A CTV will assist the CLV by deploying the personnel and equipment to conduct preparatory and completion tasks on the offshore substation, while an installation support vessel (ISV) may also be used to support cable laying. The CLV will then sail back to collect the second export cable, before repeating the load-out and cable laying procedure as described above.

8.4.1.3 Post-lay activities

A combination of jetting, mechanical cutting and CFE will be used to bury the cables once cable laying is completed. Jetting will be used for cable burial in sandy soil conditions, while mechanical cutting will be used where hard soils are encountered. CFE will be used in the transition between nearshore and offshore water depths, as well as in the last 75 m of the cable corridor leading up to the offshore substation. Each cable will be buried in separate runs, and both jetting and mechanical cutting can be performed using the same multipurpose ROV, while jetting, mechanical cutting and CFE will all be deployed and operated from a TSV or ISV.

Jetting will be used to install the export cables from the coastline out to approximately 730 m offshore (KP 0.46–1.19, Figure 8.3). The jetting tool will use high-powered water pumps feeding purpose-built jet-legs, which liquefy an area of the seabed around the jets thereby forming a trench. As the ROV moves forward, the cable is then lowered into the trench. Burial by jetting may require multiple jetting passes per cable in order to reach the target burial depth below stable seabed. The width of the seabed affected by the burial operation depends on the seabed conditions and is approximately 1 m in clay and 2 m in sandy sediment.

CFE will be used to bury the export cables between approximately 730–1,150 m offshore (KP 1.19–1.6, Figure 8.3). CFE is expected to form a trench up to 8.5 m wide and 1.5 m deep, into which each export cable will be lowered. CFE is also expected to be used to bury the last 75 m of each export cable next to the offshore substation.

The remaining length of export cables, between approximately 1,150–28,500 m offshore, will be buried either via jetting or mechanical cutting, the latter using a cutting head to loosen the sediment directly below the cable. Both methods ensure that sediment is only loosened so much that the cables can sink down into the seabed, before the sediment resettles on top of the cable again. The exact lengths where jetting or mechanical cutting will be used will depend on the exact nature of the soil conditions present along the export cable routes.

Burial activities are expected to progress at a rate of 50–350 m/hour. Following jetting and mechanical cutting, it is expected that the export cables will be reburied by natural sedimentation. The area of disturbed seabed during cable-laying in scenario 1 is 106,415 m^2. Table 8.4 summarises the indicative lengths where jetting, mechanical cutting and CFE will be used, including the width of seabed affected during cable burial activities.

Table 8.4: Area of seabed affected during the installation for both export cables in scenario 1.

Method	Sediment type	Seabed width affected (m)	Length (m)	Area of seabed disturbed (m^2)
Mechanical cutting	Clay	1	18,000	18,000
Jetting	Sand	2	40,000	80,000
CFE	Sand/clay	8.5	990	8,415

The total area of disturbed seabed during export cable installation by scenario 1 will then be approx. 306,000 m^2 (Table 8.3 for seabed preparation and Table 8.4 for post-lay activities).

8.4.1.4 Installation time schedule

In scenario 1, the installation of two 275 kV export cables will be completed over a period of approximately 7 months, excluding weather down-time. The total estimated timeframe for the key installation activities is shown below:

Seabed preparation:	28 days
Load out and cable laying:	50 days
Cable burial:	75 days

All timeframes are based on a P50 schedule, which represents the most likely scenario, except the timeframe for seabed preparation, which is conservatively estimated to require up to 28 days in total.

8.4.2 Scenario 2: Cable burial without dredging

8.4.2.1 Seabed preperation

In scenario 2, seabed preparation comprises pre-engineering surveys and route clearance using a pre-lay grapnel run and boulder relocation. The grapnel run involves pulling a grapnel train along the seabed in order to hook and remove debris (e.g. old wires or fishing nets).

Boulders will be collected using a boulder grab system. Boulders will be relocated locally outside of the planned cable route (but inside the cable corridor). The grapnel run and boulder relocation will be carried out using a trenching support vessel (TSV), ISV or similar. The relocation of rocks will lead to a permanent change in the seabed, whereby rocks with a diameter of approximately 0.5-3.0 m will be moved leading to local changes in the seabed. Approximately 300 boulders in total are expected to be relocated during the construction phase for the entire offshore wind farm.

8.4.2.2 Cable laying

Following seabed preparation, the CLV will begin the cable laying procedure by approaching the shoreline, from where the first export cable will be floated in toward landfall from the vessels turntable. Several smaller guidance vessels will be used to ensure the floats remain in position as the cable approaches landfall, after which it will pass onto pre-installed rollers on the beach prior to being pulled into the transition joint bay. The CLV will then proceed within the defined cable corridor toward the offshore substation platform, continuously laying export cable onto the seabed. The second cable end will be cut to the required length and lowered to the seabed. The cable will then be pulled through the CPS and up through the J-tube, where it will be secured on the hang-off on the substation cable deck on the offshore substation. A CTV will assist the CLV by deploying the personnel and equipment to conduct preparatory and completion tasks on the offshore substation, while an installation support vessel (ISV) may also be used to support cable laying. The CLV will then sail back to collect the second export cable, before repeating the load-out and cable laying procedure as described above.

8.4.2.3 Post-lay activities

In scenario 2, installation of the export cables will use a combination of jetting, mechanical cutting and CFE to bury the cables to target burial depths of between 1.5–3.0 m.

Jetting will be used to install the export cables from the coastline out to approximately 740 m offshore (KP 0.46–1.2, Figure 8.3) to a target burial depth of approx. 3 m. Burial by jetting may require multiple jetting passes per cable in order to reach the target burial depth, with the width of the seabed affected by the burial operation approximately 1 m in clay and 2 m in sandy sediment.

CFE will be used to bury the export cables between approximately 740–1,240 m offshore (KP 1.2–1.7, Figure 8.3). CFE is expected to form a trench up to 8.5 m wide and 3 m deep, into which each export cable will be lowered. CFE is also expected to be used to bury the last 75 m of each export cable next to the offshore substation, with burial here expected to approx. 1.5 m.

The remaining length of export cables, from approximately 1,240–28,500 m offshore, will be buried either via jetting or mechanical cutting. The exact lengths where jetting or mechanical cutting will be used will depend on the nature of the soil conditions present along the export cable routes. For example, between 1,240–3,040 m offshore (KP 1.7–3.5, Figure 8.3), the target burial depth when jetting will be to approximately 2.5 m while for mechanical cutting the target burial depth will be 1.5 m. For the remaining length out to the substation (3,040–28,500 m), the target depth will be 1.5 m for both jetting and mechanical cutting.

Burial activities are expected to progress at a rate of 50–350 m/hour. Following jetting and mechanical cutting, the export cables are expected to be reburied by natural sedimentation. The total area of disturbed seabed during installation in scenario 2 is 102,000 m^2. Table 8.4 summarises the indicative lengths for jetting, mechanical cutting and CFE without dredgning, including the width of seabed affected during cable burial activities.

Table 8.5: Area of seabed affected during the installation for both export cables in scenario 2.

Method	Sediment type	Seabed width affected (m)	Length (m)	Area of seabed disturbed (m^2)
Mechanical cutting	Clay	1	21,000	21,000
Jetting	Sand	2	35,500	71,000
CFE	Sand/clay	8.5	1,150	9,775

8.4.2.4 Installation time schedule

In scenario 2, the installation of two 275 kV export cables will be completed over a period of approximately 7 months, excluding weather down-time. The total estimated timeframe for the key installation activities is shown below:

Seabed preparation: 11 days
Cable laying: 15 days
Cable burial: 46 days

All timeframes are based on a P50 schedule, which represents the most likely scenario.

9. Offshore construction logistics

This chapter describes key details regarding site preparation and access, the deployment of safety markings around the site, and emissions during construction.

9.1 Access to site and safety zones

The installation and commissioning of Thor OWF is scheduled to take place throughout the year. Construction activities are expected 24 hours per day 7 days a week until commissioning is completed.

To optimise the construction program, the installation of wind turbines, wind turbine foundations, cables and the substation platform will be undertaken concurrently across the site, with approximately 30-60 vessels (including, but not limited to, HLVs, jack up, CTVs, ISVs, tugs/barges, rock placement, CLVs, trenching, UXO/boulder clearance) expected onsite at any given time throughout the construction phase, depending on final concepts from installation contractors.

A safety zone of approximately 500 m will be established around the Thor OWF site throughout installation and commissioning. This will ensure safety of project personnel and all third parties operating at sea, while preventing the risk of damage to the wind farm in the event of collisions. The exact safety zone will be agreed with the Danish Maritime Authority prior to construction. A dynamic 500 m safety zone will also be established around cable laying and installation vessels during the progressive installation of the export cables.

Third parties will be excluded from all safety zone established during construction, which will be marked in accordance with the requirements from the Danish Maritime Authority (section 9.2). If navigation between a port and the offshore wind farm in connection with work activities crosses a sea-lane, the Danish Maritime Authority may establish a navigation corridor which work vessels must use. In addition, 1-4 guard vessel(s) will be deployed to assist non-project vessel traffic in the vicinity to maintain the safety on the construction site.

Furthermore, helicopters will be used during the installation of the offshore substation platform, with between 4–8 helicopter visits (of approx. 3 hours of flight time per visit) anticipated during installation and commissioning.

9.2 Lighting and markings of construction site

Temporary work area markings will be deployed around the entire OWF prior to, and throughout the duration of, construction works in order to establish an approximate 500 m safety zone around the OWF. The temporary markings will comprise yellow buoys with flashing lights (Fl(3)Y10s) with an effective illuminating power of at least two nautical miles (a minimum of 10 candela). All light buoys will be fitted with yellow stop cross marks, radar reflector and reflector strips, while ownership information will appear on each light buoy and mooring.

Before the temporary work area markings are deployed, the Danish Maritime Authority will approve the number, location, type and size of the buoys. Changes may not be made to the marking without prior approval from the Danish Maritime Authority.

The Danish Maritime Authority will be notified at least six weeks prior to establishment of the markings and will be informed of the exact location of the marking. There should be a maximum of 2 nautical miles between each safety buoy around the OWF site.

The temporary work area markings will be deployed in the OWF by supporting vessel. It is expected that these will be deployed approximately 3 months before the first offshore installations and be demobilised 1 month after all permanent markings are in place.

9.3 Consumables

The construction and commissioning of Thor OWF will require diverse offshore vessels for different operations. Offshore vessels are expected to be powered using marine gas oil (MGO), with each vessel type characterised by different fuel consumptions. The estimated consumption of MGO through the construction and commissioning of Thor OWF are shown in Table 9.1.

Table 9.1: Estimated consumption of marine gas oil (MGO) from the use of offshore vessels during the construction of Thor OWF.

Operation	**Vessel type**	**MGO per day (Metric Ton)**	**Days**	**Total MGO (Metric Ton)**
Site preparation				
Boulder Clearance / PLGR	Installation Support Vessel (ISV)	10	92	920
Export cables				
Landfall (HDD)	Jack-Up	3	20	60
Cable laying	Cable Lay Vessel (CLV)	10	120	1,200
Trenching	Trenching Support Vessel (TSV)	10	60	600
Pull-in	Crew Transfer Vessel (CTV)	5	20	100
Testing & termination	Crew Transfer Vessel (CTV)	5	20	100
Inter-array cables				
Route Preparation	Installation Support Vessel (ISV)	10	40	400
Cable laying	Cable Lay Vessel (CLV)	10	94	940
Trenching	Trenching Support Vessel (TSV)	10	104	1,040
Testing & termination	Installation Support Vessel (ISV)	10	102	1,020
Tower prep. & pull-in	Installation Support Vessel (ISV)	10	40	400
Offshore substation				
Installation: Topside+Jacket	Heavy Lift Vessel (HLV)	20	10	200
Commissioning	Jack-Up	3	65	195
Foundations				
Monopile Installation	Heavy Lift Vessel (HLV)	17	95	1615
Secondary structure installation	Jack-Up / Geared Vessel	10	95	950
Scour Protection / rock beam	Rock Installation Vessel	10	100	1000
Wind turbines				
Installation	Jack-Up	15	170	2,550
Commissioning	Service Operation Vessel (SOV)	10	200	2,000
Other				
General Site Logistics	Crew Transfer Vessel x2 (CTV)	10	550	5,500
Wind turbine crew transfer	Crew Transfer Vessel x2 (CTV)	10	200	2,000
Total estimated MGO usage during construction and commissioning of Thor OWF				23,090

10. Wind farm operation and maintenance

Once the installation and commissioning of Thor OWF is complete, the wind farm will undergo periodic inspection, maintenance and servicing relating to its operation over the lifetime of the project. Operation and maintenance activities include both scheduled and unscheduled work on the wind turbine generator and foundations, the substation platform (both the foundation and topside structure), the inter-array cables and the export cables.

Operation and maintenance of Thor OWF will occur 24 hours per day, 365 days per year, with access to the site required at any time. Routine activities will typically be planned between the hours of 06:00 and 19:00, while any necessary jack-up operations may occur at any time of day (00:00–24:00). For annual maintenance, a SOV is expected to be used. The SOV will stay within the OWF area throughout the duration of the service period, with port calls to Thorsminde not expected during these periods.

10.1 Access to site and safety zones

A 200 m safety zone around all cables will be established, including restrictions against anchoring which can be otherwise intrude into the seabed. The project must comply with the legislation regarding the protection of sea cables and submarine pipes (BEK nr 939 af 27/11/1992), with protection zones identified and agreed upon with the Danish Maritime Authority.

Prohibited entry zones for non-project vessels around individual wind turbine foundations are not expected. However, the specific safety zones will be determined by the Danish Maritime Authority.

10.2 Inspection, service and maintenance activities

10.2.1 Wind turbine generators and foundations

Operations servicing the wind turbine generator and foundation will be executed by using a SOV and/or CTV. The SOV has a size of an offshore supply vessel and will stay within the OWF throughout the service period, with port calls expected approximately every 2 weeks to larger harbours only e.g. Esbjerg, Hvidesande or Thyborøn. CTVs will be used to transport turbine technicians in and out from the service harbour at Thorsminde to Thor OWF. It is expected that there will be 1 permanent CTV available during normal operations, with 2 CTVs onsite during service periods.

Further to above mentioned vessels, each wind turbine will be equipped with a heli-hoist platform to enable hoisting of the turbine technicians via helicopter. The heli-hoist platform will be used when the operation and maintenance team find it more suitable, compared to using CTV or SOV.

Each wind turbine will undergo scheduled inspection and maintenance to assess the level of wear in key components and to check e.g. lubrication, fluids and filters. Specific activities will follow those prescribed by the manufacturer within the service and maintenance documentation, with each wind turbine generator expected to be serviced via SOV once per year, with servicing lasting approximately 2.5 day.

Periodic visual inspections of both the above- and below-water foundation structure will be carried out for each wind turbine. Above-water inspections will occur once a year at the same time as minor repairs and scheduled and unscheduled maintenance. All structural inspections, including lifting operations and the certification of access equipment, are expected to be completed within the same visit. The inspection of above-water structures and minor repairs and scheduled/unscheduled works combined will last 1 day and will be carried out in spring. Below water inspection of turbine foundations will be performed during an annual ROV campaign where approximately 25 % of the foundations will be inspected. The inspection will last approximately 5 days in total and will occur in either the spring or summer. The above will all be planned in accordance with the manufactures service and maintenance documentation.

10.2.2 Offshore substation platform

Monthly or quarterly visits are planned to the offshore substation platform throughout the lifetime of Thor OWF. Operations servicing the substation platform will be executed using CTVs. These will be used to transfer service personnel to both the offshore turbines and substation platform from the Port of Thorsminde. The substation platform will also be equipped with a heli-hoist platform to enable hoisting operations.

The servicing and maintenance of high-voltage equipment is expected to require two annual service visits, with 10 days anticipated during a spring visit and 3 days required during the autumn. This includes all scheduled and unscheduled maintenance, as well as minor repairs.

The inspection of ancillary electrical (e.g. communications and lighting systems), ancillary support systems (e.g. back-up generators, fire safety systems, heating and ventilation), structural components (e.g. heli-hoist and above-water substation foundations) and the testing, certification and maintenance of lifting equipment will collectively require an additional two annual service visits to perform. These will each last approximately 5 days and will be held in the spring and autumn and includes all scheduled and unscheduled maintenance, as well as minor repairs. Below water inspection of the substation foundations will also be performed, potentially during an annual ROV campaign of the entire Thor OWF. This will be defined by an overall ROV strategy.

10.2.3 Cables

In the event that an inter-array or export cable fails, or a fault is identified, cable repair, replacement, re-burial and re-protection activities may be required. A cable engineer and diagnostic equipment may first be deployed to localise faults in the cabling in the event a defect occurs. Fault finding will require the use of an SOV and CTV.

If a fault requires the full replacement of a cable, cable engineers will first remove the cable protection before decoupling the cable (e.g. from wind turbines or transformers) and removing it entirely. New cable will then be laid using a CLV, prior to re-burying of the cable occurring from an TSV. Re-burial may occur by means of jetting, where a ROV equipped with high-powered water pumps liquefies the sediment below the cable, allowing the cable to sink into the seabed (see section 7.4.3). Where damaged cable can be repaired, a cable engineer will first remove the faulty section after which the new section of cable will be jointed together to existing cabling. Depending on the location of the faulty cable, for example if it is a mid-section cable or a cable attached to either a wind turbine or substation, CLVs, CTVs or SOV may be required.

10.2.4 Seabed surveys

A geophysical survey campaign is planned each year during either spring or summer. The need for an annual geophysical survey will be assessed after some years to determine the future inspection intervals.

Each geophysical survey campaign will consist of both scheduled and unscheduled surveys including foundation scour surveys, cable route surveys, cable depth of burial (DoB) survey, and bathymetric surveys for e.g. jack-up operations. Geophysical surveys are expected to be carried out using methods such as side scan sonar (SSS) and multi beam echo sounder (MBES), while DoB surveys will be performed using a cable tracker.

Each annual geophysical survey campaign will be executed using seabed survey vessel and are anticipated to be carried out over approximately 30 days.

10.2.5 Helicopters during operation

When the substation is in operation, up to 12 service visits (of approx. 3 hours of flight time per visit) by helicopter per year are expected, although the exact number of visits will likely vary depending on the need for service and maintenance. It is expected that more frequent visits will be required during the first year of operation. It is estimated that wind turbine servicing will require approximately 172 hours of flight time by helicopter. The calculation is based on a yearly average over 6 years from a windfarm with the same set up as planned for Thor OWF.

The fuel consumption for helicopter journeys is estimated at 215 litres per hour of operation, resulting in an estimated annual consumption of aviation fuel of approximately 36 tons/year.

10.2.6 Inspection, servicing and maintenance summary

Table 10.1 summarises the type, number and duration of annual visits expected for the operation and maintenance of Thor OWF based on the use of sea-going vessels. The summary does not include visits relating to troubleshooting.

Table 10.1: Summary of the visit type, number of visits per year and the total number of days anticipated for inspecting, servicing and maintaining Thor OWF.

Operation and maintenance	Total annual visits	Total duration (days)
Wind turbine		
Generator (by sea)	72	180
Foundation (above water)	72	72
Foundation (below water)	18	90
Offshore substation platform		
High-voltage systems	2	13
Ancillary features, structural components, certification	2	10
ROV inspection	1	5
Seabed surveys	1	30

10.2.7 Consumables

Table 10.2 summarizes the quantity of consumables during the operation and maintenance of Thor OWF as well as the change frequency and consumption per year.

Table 10.2: Summary of approximate quantity, change frequency and yearly consumption of consumables for Thor OWF project.

Consumable	Quantity	Change frequency (months)	Consumption/year
Yaw gear oil (litres)	30	12	30
Grease (kg)	96	12	96
Oil filter (pcs)	3	12	3
Dust - air filter (pcs)	11	12	11
Yaw oil exchange (litres)	125	60	25
Hydraulic oil exchange (litres)	880	60	176

10.3 Emissions

The use of marine vessels and helicopters during the inspection and maintenance of Thor OWF results in emissions to the atmosphere. Emissions may also arise from the use of back-up diesel generators on the substation platform, however generators are only in operation in emergency situations or for limited amounts of time for testing purposes.

Regarding the maintenance of foundations, it will be ensured that the technique employed for marine growth removal does not damage the underlying paint coating so as to result in the release of paint particles to the marine environment. Thus, the use of brushes will not be allowed for marine growth removal.

11. Wind farm decommissioning

Thor OWF will be decommissioned after 30–35 years. As set out in Annex 3.2 of the Concessions Agreement, the concessionaire is obliged to restore the area to its former condition, including carrying out the necessary remediation and clean up of the area, as well as decommissioning and completely disposing of the offshore electricity production plant. In certain cases, it can be necessary for part of a monopile to remain in-situ. However, remaining components must remain below stable seabed so that they are not exposed to the natural dynamic changes in sedimentation.area.

A decommissioning plan is to be submitted to the Danish Energy Agency no later than 2 years prior to the expiry of production at Thor OWF. A detailed assessment of the decommissioning plan and its expected environmental impacts must be submitted along with the decommissioning plan in accordance with legislation relevant at the time of decommissioning. The decommissioning of Thor OWF will therefore undergo an environmental impact assessment before decommissioning begins.

It is unknown at this stage how the offshore components may be decommissioned. However, the methods for decommissioning must follow best practise and the legislation at that time. Due to the 30-35 year timeline of Thor OWF, it is possible that new technologies for decommissioning may be developed and deployed.

The following sections provide a description of the current best practices with respect to decommissioning of OWFs and associated components.

11.1 Extent of decommissioning

The objectives of the decommissioning process are to minimize both the short- and long-term effects on the environment whilst making the sea safe for others to navigate. It is anticipated that the following level of decommissioning on the wind farm will be performed:

1. Wind turbines, including blades, the nacelle and tower will be removed completely.
2. Structures and substructures will be completely, or partially removed to under the level of stable seabed.
3. Inter-array and export cables will be completely removed.
4. Scour protection will be completely removed.
5. Reestablishment of the previous conditions in the area incl. the necessary clearing and cleaning.

11.2 Wind turbines

Decommissioning activities are largely expected to follow the wind turbine installation and commissioning operations, albeit in reverse. One jack-up vessel, 1–2 SOVs and 1-2 CTVs are therefore expected to be used through the decommissioning stage, with an operational time of 24-36 hours per turbine.

The intended lifetime of the wind farm is 30-35 years, during which improved decommissioning capabilities are expected to be available. For each individual wind turbine, the blades, nacelle and tower will be completely removed.

Recycling and other sustainable opportunities are currently being pursued in partnership with the original equipment manufacturers (OEMs), considering elements such as blade recycling, and recyclable blades will be used on 40 out of the 72 wind turbines. Tower sections, being mainly steel, are already largely recyclable, as is the high voltage equipment such as switchgear and transformers.

11.3 Wind turbine foundations

If foundations are to be partially removed, each monopile will be removed down toseveral meters below the seabed using internal or external pile cutting tools. Typically, seabed material at the exterior or interior base of the monopile is removed first, prior to an ultra-high pressure abrasive water jet tool being applied to cut through the steel. Decommissioning by cutting is expected to use the same installation spread as required for installation (see section 5.5.2).

Due to the expected 30-35 year lifetime of the Thor OWF, it is possible that new technologies for the decommissioning of wind turbine foundations may be used, including the recovery of the complete monopile structure using either hydraulic removal or vibration. Such techniques do not rely on piling by hammer, and as such, the removal of monopiles using e.g. vibration is expected to minimize any impact from noise.

All steel, cast iron and other metal components from the foundations will be scrapped and recycled.

11.4 Substation

The decommissioning of the offshore substation platform is anticipated in the following order:

1. Disconnection of submarine cables from the substation and associated hardware.
2. Removal of all fluids on the platform, including oils, lubricants and gasses.
3. Removal of the substation topside from the foundation jacket.
4. Removal of jacket foundation from the piles around seabed level.

First, the substation is disconnected from submarine high voltage cables and all fluids from the platform are removed.

Next, the substation topside will be cut free (e.g. using an abrasive water jet tool) from the foundation jacket and lifted off using a HLV vessel or similar, after which the substation topside will likely be transferred to a towed transport barge for removal. Disconnection of high voltage cables and the cutting and removal of the topside is expected to be supported by a similar vessel spread as that used for installation and commissioning (e.g. SOVs, CTVs). Once the substation topside is removed, removal of the foundation jacket can begin.

The removal of jacket foundations is expected to follow the same procedure as that outlined for other monopile foundations (see section 11.3), with ultra-high pressure abrasive water jet tools used to cut the individual piles, or using hydraulic removal or vibration. If cut, the piles are expected to be removed down to, or several meters below, the seabed. It is expected that all steel components retrieved will be sold for scrap and recycled.

The decommissioning of the jacket foundation is largely expected to require use of a similar installation vessel as for installation (e.g. HLVs, SOVs and CTVs).

11.5 Inter-array and export cables

In order to completely remove inter-array and export cables, the cable recovery process would essentially be the reverse of the cable laying operation. In this case, the decommissioning of cables is expected to be supported by a similar vessel spread as that used for installation, including CTVs, SOVs and a CLV. During decommissioning, the cable handling equipment would work in reverse gear, with the cable either being coiled into tanks onto a vessel or guillotined into sections approximately 1.5 m long immediately as it is recovered. These short sections of cable would be then stored in ships or open containers on board a vessel for later disposal through appropriate routes for material reuse, recycling or disposal. For example, it is anticipated that copper and aluminium will be sold for scrap to be recycled.

12. Waste management

Waste will be generated during the installation, operation and decommissioning of the Thor Offshore Windfarm, with the type of waste and its handling discussed below in relation to each phase of the project.

12.1 Construction

During the construction phase, various types of waste will be generated, including metal scraps, discarded bolts, rope, wooden pallets, plywood sheets and packaging. Experience from construction works at other offshore wind farms also shows that small amounts of cable scrap waste is expected, although cable scrap can be recycled.

Household, combustible, and sanitary waste will also be generated during the construction phase from crews based on the various installation vessels, while the ships themselves will procude waste oil and chemicals.

In accordance with the client's contracts with the contractors, the contractors must dispose of all the above-mentioned waste in accordance with applicable local and international regulations. It is expected that the waste will be handled within EU ports, including Danish ports.

Within the EU, ports are obliged to receive waste from ships, cf. Directive 2019/883 of the European Parliament and of the Council of April 17, 2019 on port reception facilities for the delivery of waste from ships. In addition, waste from ships is also regulated internationally under the International Convention for the Prevention of Pollution of Ships (MARPOL). This convention prohibits the dumping of waste and includes recommendations for sorting waste for delivery to ports.

In the Danish territorial waters and the Danish exclusive economic zone (EEZ), the prohibition of dumping of waste and the handling of waste and wastewater from ships is contained in the Executive Order of the Act on the Protection of the Marine Environment (LBK nr 1032 af 25/06/2023) and the executive orders issued pursuant to this, in particular, the Executive Order on the discharge of waste from ships and platforms (BEK nr 537 af 22/05/2017), the Executive Order on the discharge of sewage from ships and platforms outside Danish territorial waters and the Baltic Sea area (BEK nr 538 af 22/05/2017) and the Executive Order on the discharge of oil from ships (BEK nr 539 af 22/05/2017). Additionally, the Ballast Water Management Convention (BWM Convention) aims to prevent the spread of potentially harmful aquatic organisms and pathogens in ships' ballast water through the so-called D1 and D2 standards. The D1 standard requires ships to exchange ballast water in open seas, away from coastal areas, while the D2 standard sets limits for the amount of orgamisms to be discharged in ballast water, and usually involves installing a ballast water management system. As of September 2024, the D2 standard will apply to all ships registered under contracting Parties to the BWM Convention.

For waste delivered to Danish ports during the construction phase, pursuant to the executive order on reception facilities for waste from ships (BEK nr 577 af 06/05/2022), sorting must take place at the port, after which the waste will be included in the municipal waste management, incl. recycling. In practice, this is often done by sorting the waste on the ships according to the recommended categories in MARPOL and delivering it to the port in specially designed containers and bins, after which the port ensures that the waste is included in the municipal waste management. The waste types and associated quantities arising during the construction phase are expected to be included in municipal waste management.

12.2 Operation

Waste generated in connection with the general operation and maintenance of the offshore wind farm includes waste from oil changes, oil filters and other waste oils (section 10.2.7). In addition, waste will also be generated when replacing spare parts, changing air filters etc (section 10.2.7). Furthermore, the crew of the ships servicing the wind farm will produce household waste, combustible waste and other sanitary waste. In addition, the ships will also produce oil and chemical waste. As Thor Offshore Windfarm will begin operation in 2027, the management of ballast water during the operational and maintentence will be goverened by the BWM Conventions D2 standard (see section 12.1).

Operation and maintenance is expected to be handled primarily from the Port of Thorsminde. The amount of waste is assessed to be limited, and all waste during the operational phase from the offshore wind farm can be handled under municipal waste management, including in accordance with the Executive Order on reception facilities for waste from ships (BEK nr 577 af 06/05/2022), according to which waste from ships must be sorted at the port and then included in municipal waste management, see section 12.1.

12.3 Decommissioning

Waste will be generated during the decommissioning of the wind farm itself, including from the offshore cables. The type of waste and its management is discussed in more detail in section 11.

This will ensure that the vast majority of the project's materials will be scrapped and reused. It is known that cable scrap can be recycled, and it is estimated that other materials from the wind turbines and foundations will be recycled in line with the general development in the area. Furthermore, recyclable blades will be used on 40 of the 72 wind turbines (RWE, 2023), allowing for separation and recycling of various components in the wings.

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Appendix 1

Coordinates for wind turbine and substation positions

A list of the coordinates for the 72 wind turbine positions are listed in the table below along with the water depth at the position.

WTG ID	Eastings (m)	Northings (m)	Water depth (m)
T01	418705.04	6256204.98	-26.9
T02	419668.1	6257241	-27.5
T03	421108.9	6257188	-27.2
T04	417751.18	6255109.74	-25.5
T05	419961.47	6254591.94	-27.9
T06	421342.21	6255475.77	-28.7
T07	422788.75	6254894.17	-27.5
T08	416546.97	6253744.21	-24.8
T09	418701.54	6253807.42	-25.4
T10	415509.2	6252575	25.2
T11	417436.46	6252585.45	-25.2
T12	419904.89	6252587.44	-25.9
T13	421825.65	6252996.28	-27.6
T14	416066.47	6251122.84	-26.5
T15	418459.10	6250820.00	-29.8
T16	421822.23	6250921.85	-27.9
T17	423507.20	6251815.30	-28.8
T18	415957.85	6249589.71	-28.7
T19	417504.35	6249767.50	-30.0
T20	419904.46	6250003.64	-26.9
T21	421591.13	6249226.61	-24.4
T22	423266.86	6250239.70	-27.2
T23	416306.14	6247938.78	-30.0
T24	417746.29	6248151.27	-27.5
T25	419921.95	6248587.66	-26.4
T26	421685.06	6247594.11	-24.9
T27	423265.21	6248719.83	-26.3
T28	415106.84	6246452.26	-30.4
T29	417504.85	6246475.39	-27.3
T30	419908.59	6246109.82	-23.9
T31	423264.04	6246748.00	-26.8
T32	411509.50	6244423.64	-29.4
T33	413235.65	6244588.17	-30.2
T34	414779.40	6244583.90	-27.6
T35	416542.72	6245033.48	-27.7
T36	418707.77	6244744.14	-26.9
T37	420862.47	6244890.14	-28.0
T38	423261.59	6245310.17	-27.0
T39	412407.30	6242589.98	-26.5
T40	414382.54	6243109.36	-26.5
T41	417022.04	6243226.22	-25.3

T42	418939.03	6243309.00	-25.7
T43	421590.31	6243530.83	-30.2
T44	423262.86	6243891.27	-27.5
T45	412465.57	6240673.92	-29.9
T46	413905.03	6241341.02	-25.3
T47	415588.45	6241596.64	-27.1
T48	417506.53	6241800.25	-29.0
T49	419670.09	6241832.63	-25.0
T50	422065.35	6241906.59	-28.6
T51	423506.14	6242106.63	-26.7
T52	413906.57	6239694.23	-27.0
T53	416301.68	6239920.53	-28.5
T54	417986.31	6239966.97	-26.1
T55	419900.07	6239944.13	-28.8
T56	421824.65	6239262.33	-29.0
T57	423507.31	6240161.30	-25.4
T58	413907.60	6238237.48	-29.1
T59	415341.61	6237459.38	-29.2
T60	417025.92	6237789.22	-28.4
T61	418938.96	6237941.50	-29.4
T62	421340.90	6237358.78	-26.9
T63	423745.86	6238416.13	-25.7
T64	416225.61	6235586.59	-27.3
T65	417746.59	6236208.92	-27.1
T66	420379.85	6235489.25	-26.9
T67	422663.40	6235579.25	-27.0
T68	423745.45	6236812.60	-26.7
T69	416062.6	6234153	-27.3
T70	417744.8	6234153	-27.7
T71	420858.6	6234153	-25.7
T72	423987	6234153	-26.5

Substation coordinates are listed in the table below.

Vertex ID	UTM32N_X	UTM32N_Y
1	421344.95	6246613.734
2	421373.2343	6246585.45
3	421344.95	6246557.166
4	421316.6657	6246585.45