Ανοιχτό Πανεπιστήμιο Κύπρου
Σχολή Economics and Management

Μεταπτυχιακό πρόγραμμα σπουδών Master in Business Administration (MBA in English)

Μεταπτυχιακή Διατριβή

A deep dive to the decommissioning of Borssele 1+2 offshore wind farm

Michail Seiragakis

Supervisor
Georgios Xydis

Μάιος 2022

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This Master's Dissertation was submitted in partial fulfilment of the requirements for the award of the postgraduate title on Master in Business Administration (MBA) by the Faculty of Economics and Management of the Open University of Cyprus.

Μάιος 2022

Abstract

Offshore wind is playing a crucial role to the energy transition worldwide with the power capacity installed annually being increased exponentially. Several countries rush to develop offshore wind projects to meet their energy targets to comply with the different climate convention's agreements without looking into the after-operations period. This forces project developers to secure unrealistic budgets for decommissioning works and paying excessive bank guarantees.

This study firstly analyses the current framework under which a project developer could apply for a permit for decommissioning works and the available market knowledge for this kind of activities. Subsequently, evaluates the process of decommissioning an offshore wind farm and tries to optimise it wherever possible and allowed by the regulations. Efficiency and effectiveness are the main objectives of all involved stakeholders while the regulatory, environmental, health and safety and public acceptance requirements will be respected.

A project team is composed, roles and responsibilities are assigned to be able to accomplish such a demanding assignment. Finally, a budget estimation following a selected decommissioning strategy is made showing that the initial budget estimation could be reduced by 20% when the processes are optimised and agreements are made with the government.

All data generated and analysed during this study can be provided upon request.

Περίληψη

Η υπεράκτια αιολική ενέργεια διαδραματίζει κρίσιμο ρόλο στην ενεργειακή μετάβαση παγκοσμίως, καθώς η ισχύς που εγκαθίσταται ετησίως αυξάνεται εκθετικά. Αρκετές χώρες σπεύδουν να αναπτύξουν υπεράκτια αιολικά έργα για να επιτύχουν τους ενεργειακούς τους στόχους και να συμμορφωθούν με τις διάφορεςσυμφωνίες για τη κλιματική αλλαγή, χωρίς να εξετάζουν την περίοδο μετά το πέρας της λειτουργίας του έργου. Αυτό αναγκάζει τους επενδυτές να εξασφαλίσουν μη ρεαλιστικούς προϋπολογισμούς για έργα decommissioning και τη πληρωμή υπερβολικών τραπεζικών εγγυήσεων.

Αυτή η μελέτη αναλύει αρχικά το τρέχον πλαίσιο κάτω από το οποίο ένας υπεύθυνος ανάπτυξης έργου θα μπορούσε να υποβάλει αίτηση για άδεια για εργασίες decommissioning και τη διαθέσιμη γνώση της αγοράς για αυτού του είδους τις δραστηριότητες. Στη συνέχεια, αξιολογεί τη διαδικασία decommissioning ενός υπεράκτιου αιολικού πάρκου και προσπαθεί να το βελτιστοποιήσει όπου είναι δυνατόν και επιτρέπεται από τους κανονισμούς. Η αποδοτικότητα και η αποτελεσματικότητα είναι οι κύριοι στόχοι όλων των εμπλεκόμενων φορέων, ενώ θα τηρούνται οι θεσμικές, περιβαλλοντικές απαιτήσεις όπως και οι απαιτήσεις ασφάλειας όπως και η δημόσια αποδοχή.

Μια ομάδα έργου δημιουργείται, ρόλοι και ευθύνες ανατίθενται για να μπορέσει να ολοκληρώσει μια τόσο απαιτητική αποστολή. Τέλος, γίνεται μια εκτίμηση του προϋπολογισμού μετά από μια επιλεγμένη στρατηγική decommissioning που δείχνει ότι η αρχική εκτίμηση του προϋπολογισμού θα μπορούσε να μειωθεί κατά 20% όταν βελτιστοποιηθούν οι διαδικασίες και συναφθούν συμφωνίες με την κυβέρνηση.

Όλα τα δεδομένα που δημιουργούνται και αναλύονται κατά τη διάρκεια αυτής της μελέτης μπορούν να αποσταλούν κατόπιν αιτήματος.

Acknowledgements

Throughout the writing of this dissertation I have received a great deal of support and assistance.

I would first like to thank my supervisor, Professor Georgios Xydis, whose expertise was invaluable in formulating the research questions and methodology.

Special thanks are also owed to my friends and family for their sympathetic ear and wise counsel throughout the past nine months.

List of Abbreviations

ABEX	Abandonment Expenditure
AIS	Automatic Identification System
CAGR	Compound Annual Growth Rate
CAR	Contractor's All Risk
CPS	Cable Protection System
DP	Dynamic Position
EEZ	Exclusive Economic Zone
HV	High Voltage
GW	Giga Watts
GWEC	Global Wind Energy Council
IMO	International Maritime Organisation
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ITT	Invitation to Tender
MP	Monopile
MW	Mega Watt
MWS	Marine Warranty Surveyor
NM	Nautical Miles
OSPAR	Oil Spill Prevention-Administration-Response
OWF	Offshore Wind Farm
PSV	Platform Supply Vessel
ROV	Remote Operated Vehicle
RVO	Netherlands Enterprise Agency
SGRE	Siemens Gamesa Renewable Energy
TP	Transition piece
TSO	Transmission System Operator
UXO	Unexploded ordnance
WFSD	Wind Farm Site Decisions
WTG	Wind Turbine Generator

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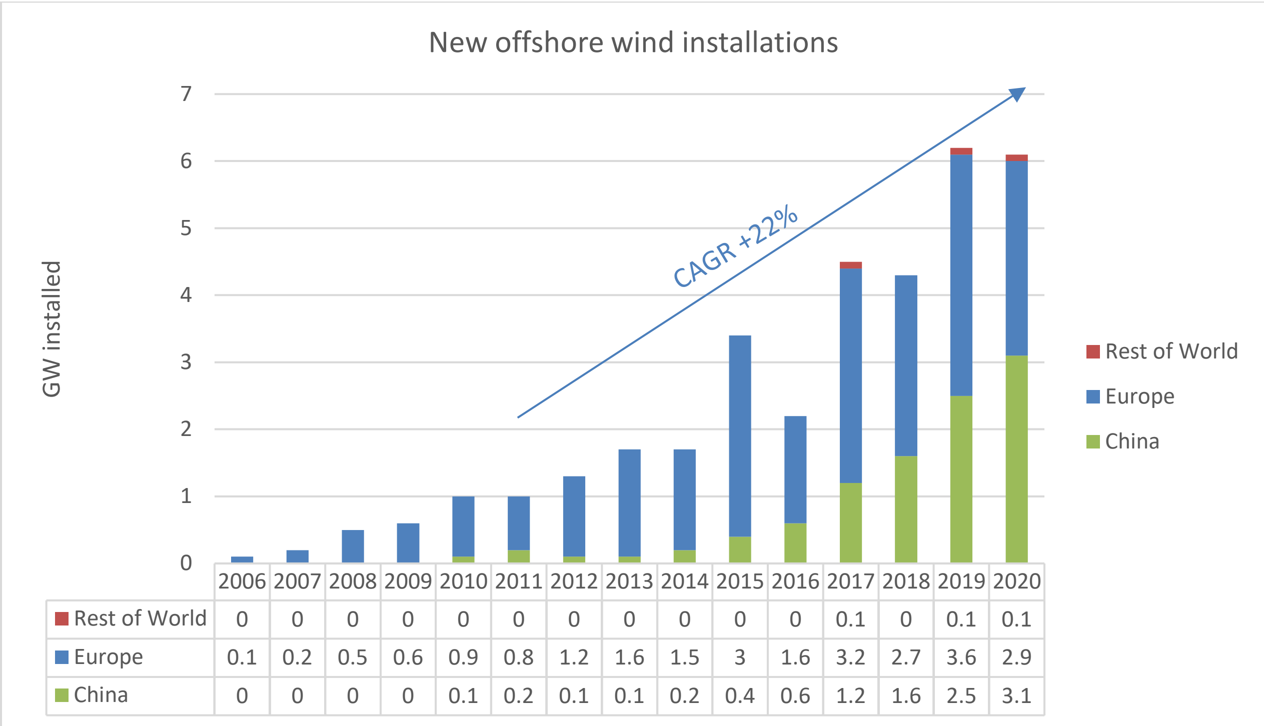
1 Introduction

1.1 Offshore wind worldwide

Offshore wind is and will continue to be a key vector in the global response to climate change. Energy production accounts for around three-quarters of global greenhouse gas emissions and will be the focal area for the climate change mitigation efforts. The global offshore market grew on average by 22% each year in the past decade, bringing total installations to 35.3 GW, which accounted for 5% of total global wind capacity as of the end of 2020 (Lee & Zhao, 2021). This growth is steady with a Compound Annual Growth Rate (CAGR) of 22% as it can be seen in Figure 1, with China and Europe being accounted for the majority of new installations.



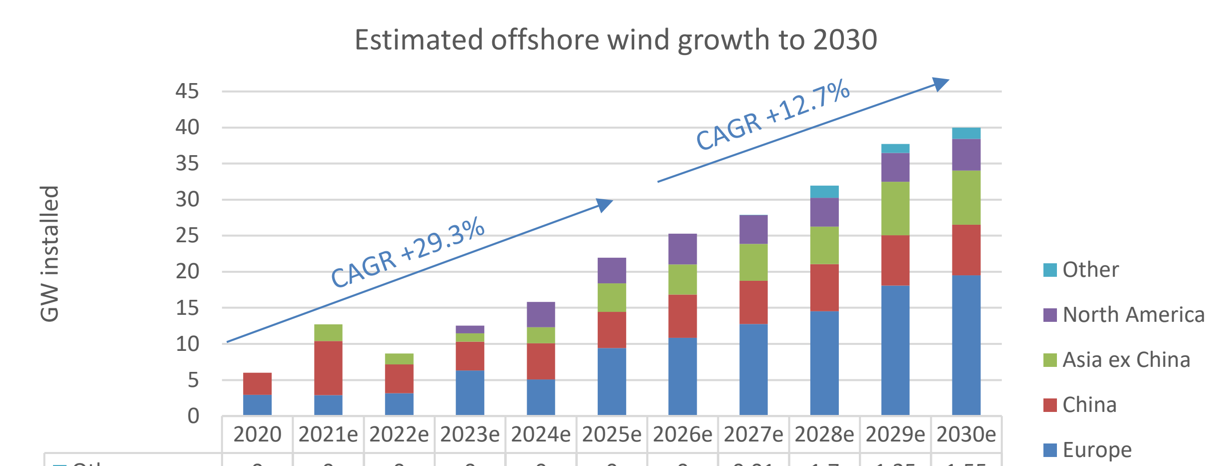
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Rest of World	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0.1	0.1
Europe	0.1	0.2	0.5	0.6	0.9	0.8	1.2	1.6	1.5	3	1.6	3.2	2.7	3.6	2.9
China	0	0	0	0	0.1	0.2	0.1	0.1	0.2	0.4	0.6	1.2	1.6	2.5	3.1

Figure 1 New offshore wind installations worldwide 2006-2020 (Lee & Zhao, 2021)

The global offshore wind market outlook to 2030 has grown even more promising over the past 12 months because of several factors such as:

- governments worldwide continue to raise their ambition levels and re-adjust their agendas with regard to climate change
- the sharp drop of offshore wind costs made it one of the most competitive energy sources
- progress continued in commercialisation and industrialisation for floating wind opening the doors of deeper seas
- offshore wind increasingly played a unique role in facilitating cross industry cooperation and decarbonisation, such as oil and gas sector transition to renewables
- war in Ukraine exposed Europe's dependency to Russia's fossil fuels

With a compound average annual growth rate of nearly 30% until 2025 and 12.7% up to the end of the decade as depicted in Figure 2 (Lee & Zhao, 2021), new annual installations worldwide are expected to exceed the milestones of 20 GW in 2025 and potentially 40 GW in 2030.



	2020	2021e	2022e	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
Other	0	0	0	0	0	0	0	0.01	1.7	1.25	1.55
North America	0	0	0	1.07	3.5	3.56	4.25	4	4	4	4.4
Asia ex China	0	2.33	1.49	1.14	2.21	3.96	4.2	5.1	5.2	7.4	7.5
China	3.06	7.5	4	4	5	5	6	6	6.5	7	7
Europe	2.94	2.89	3.17	6.31	5.09	9.44	10.84	12.74	14.55	18.07	19.53

Figure 2 Global Offshore wind growth to 2030 (Lee & Zhao, 2021)

Global wind energy council (GWEC) market intelligence expects that over 235 GW of new offshore wind capacity will be added over the next decade, bringing the total offshore wind capacity to 270 GW by 2030.

International energy agency (IEA) and international renewable energy agency (IRENA) have published out roadmaps which show that wind and solar energy supply must reach around 70% of electricity generation by 2050 to deliver the required deep emissions reductions. From now to 2050, offshore wind will scale up and become a central factor of global decarbonisation, transforming the electricity system in generation, infrastructure, flexibility and production of green fuels like hydrogen. Its application will not discriminate between emerging economies and advanced economies, nor one region of the world over another because of the development of floating wind.

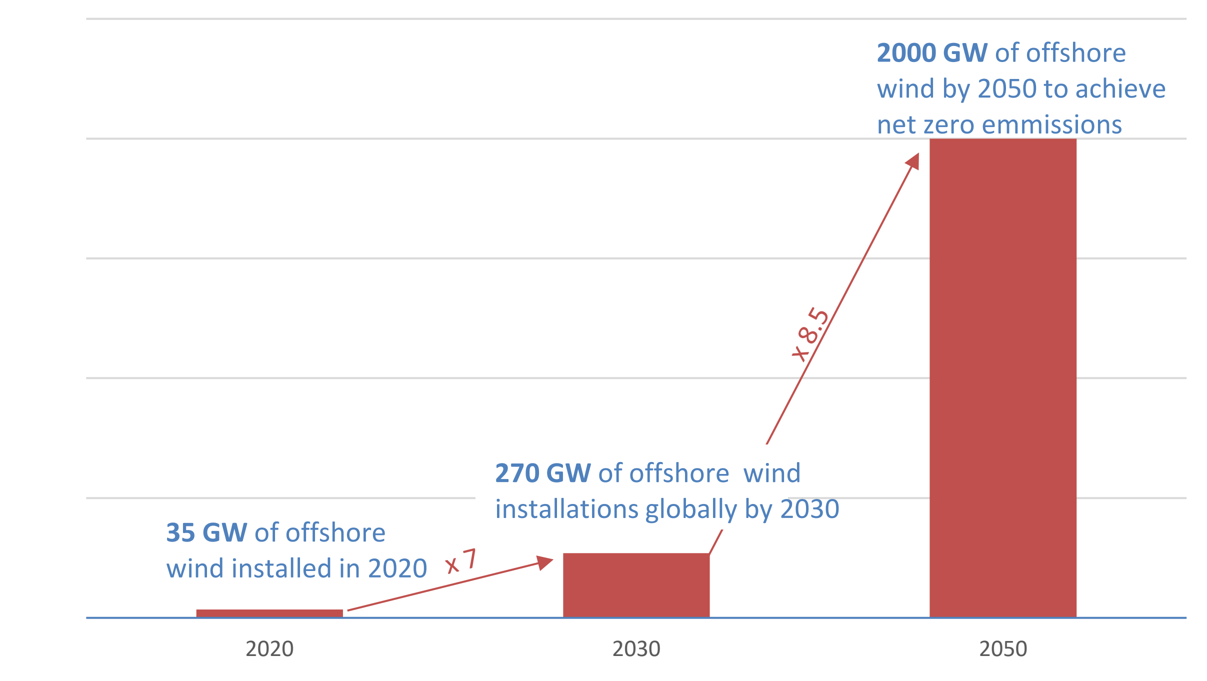


Figure 3 Closing the offshore wind gap by 2050 (Lee & Zhao, 2021)

1.2 Description of an offshore wind farm

An offshore wind farm is a power plant that contains all the facilities needed to produce electricity, transform it and supply it to the main electricity network. The main parts of an offshore wind farm are the wind turbine generators (WTG) with their foundations, the cables, and the offshore and onshore substations.

The wind turbines are nothing more than generators that convert the wind power into electricity. For economic reasons, such as reducing planning, construction, and maintenance costs, many wind turbines are installed at the same time in one location. Monopiles (MP) are one of the most common foundation designs in offshore wind construction due to their ease of installation in shallow to medium depths of water. The steel cylinder is piled into the sea floor by a specialist hydraulic hammer, as seen in Figure 4. The second most common foundation design is the jacket.

Figure 4 Installation of a monopile in Gemini Offshore Wind Farm

Once the monopile has been set in the sea bed, see also Figure 4, a transition piece is then fitted on top. The transition piece is secured carefully as it has the important job of connecting the turbine and the monopile together. The next stage is assembling the turbine tower which is craned into position and bolted together (see Figure 5 (4c_offshore, 2019)). The turbine is constructed in separate sections, split into its main components which include: tower, nacelle, rotor hub and blades. The nacelle is the master mind of the turbine because the generator, the converter, the transformer and the gearbox are located there.

Figure 5 Installation of a wind turbine in Luchterduinen Offshore Wind Farm

The electric power produced by the turbines is then transferred through cable arrangements, also named strings, to an offshore substation. The inter-array grid consists of kilometres of cables which are laid at the bottom of the sea and trenched with remote operated vehicles (ROV) to depths of 2-5 metres. The inter-array grid cables are ended at the offshore substation. The offshore substation consists of switchgears, transformers and low voltage systems and is responsible for accumulating the electricity and scaling up the voltage level so that it can be transported to longer distances onshore. Two export subsea cables are in most cases performing this task. Figure 6 represebts graphically an offshore wind farm (OWF) arrangement.

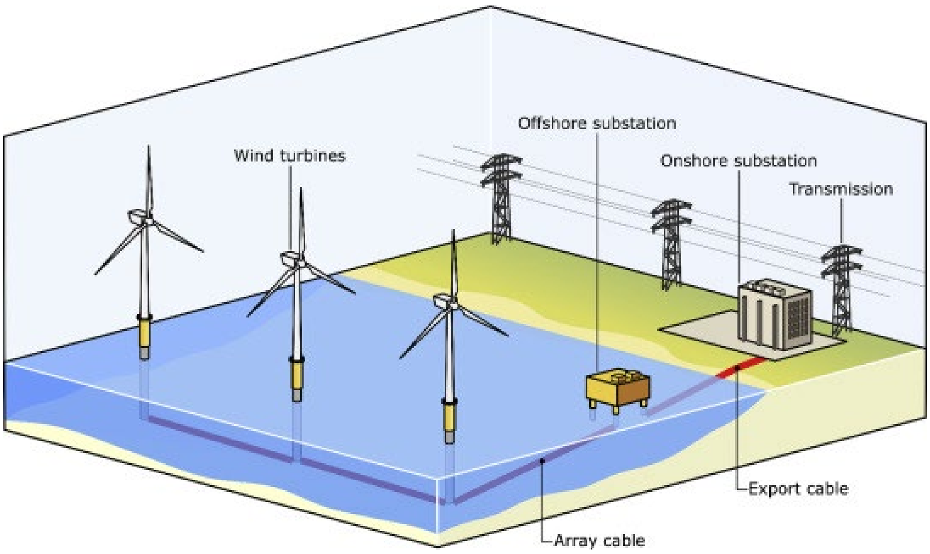


Figure 6 Graphical representation of an offshore wind farm (Letcher, 2020)

Scour protection is typically required to maintain sufficient burial of the foundations at the sea bottom. These vertical piles present a large obstruction to the water and tidal flow, therefore are prone to erosion of the surface around their base, known as scour.

To apply scour protection, the most common methodology generally employed is to lay a filter layer of small aggregate material, with maximum particle size normally around 100 mm diameter, before piling to act as temporary scour protection immediately after the pile is driven. Subsequently, heavier aggregate material is deposited over the filter layer, to permanently protect the seabed from erosion by wave, tide, or current action.

Figure 7 Sandbank OWF under construction

1.3 End of wind farm lifetime - Decommissioning

The operational life of offshore wind farms is finite, in most cases calculated to 20-25 years. The most critical components which define the lifetime of the offshore wind farm are the wind turbines and the foundations. These are designed for a specific amount of fatigue to maintain the balance between investments at the beginning of the project and lifetime at the end. When the lifetime of a wind farm reaches the end there are three options:

Lifetime extension: To extend the lifetime of a wind farm factually implicates that the wind turbine can be operated for a period of time longer than what it was originally economically designed for. Detailed evaluation has to be performed by specialised companies to all components, and minor adjustments might be required.

Re-powering: In this scenario it is assumed that wind energy is still economically attractive at the point of decommissioning, the technical integrity of the wind turbines is declining but the electrical infrastructure and possibly the foundations remain sound. By closely monitoring the structural integrity of the asset, it could be possible, subject to any necessary consents being granted, to re-use these parts of the system in a re-powering of the Wind Farm – i.e. fitting new wind turbines to the existing foundation and electrical systems.

Decommissioning: This is the ultimate step, regardless if the other steps of repowering and lifetime extension is adopted, decommissioning is unavoidable eventually. When the offshore wind farm reaches the end of its service life, the majority of the wind farm components are required to be removed.

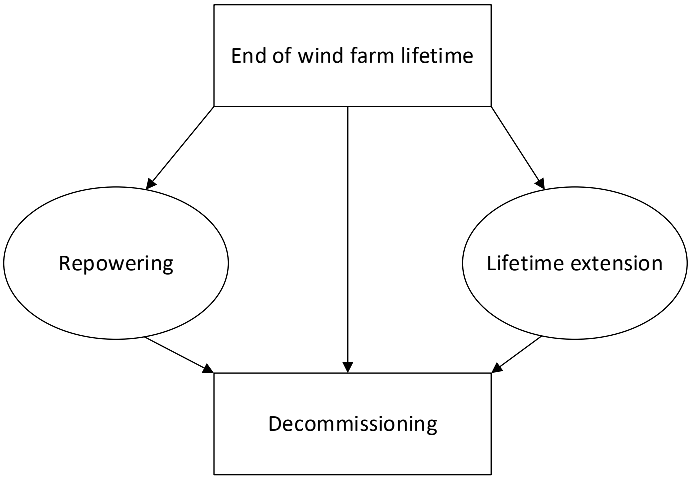


Figure 8 End of wind farm lifetime options

Decommissioning an offshore infrastructure may comprise strategies ranging from a mere abandoning over partial to full removal of the installations. However, decommissioning strategies for offshore constructions like oil and gas rigs are subject of debate because the environmental impacts of decommissioning remain yet to be fully unravelled (Fowler, 2020). Environmental concerns comprise eventual negative impacts of the decommissioning activities themselves and the removal of perceived beneficial ecosystem services facilitated by the installations. On the contrary, offshore wind farms occupy vast areas and leaving them at sea is undesirable because of future use of the area for new wind farms or other types of activities (Smyth, 2015).

International and national legislation currently provide that the decommissioning involves the complete removal of the offshore installation and all its components. Any access restrictions for fishing, navigation and recreational usage will then be revoked. Depending on the resilience of the site, the area would then return near to its original, pre-wind farm state and community structure. Nevertheless, while the removal of the monopiles may be easy, the removal of underground cables and scour protection is difficult, if at all possible. Furthermore there is no guarantee of a return to a pre-construction ecological state.

Similar to the construction of the offshore wind farm, decommissioning is also regarded as a project requiring an environmental impact assessment and an appropriate assessment when in a natural conservation area under, for example the EU Habitats Directive which will be reviewed by the governmental authorities. Hence, the developer has to demonstrate no or, at most, acceptable environmental impact of the construction, operation and decommissioning and thus show the balance of impacts and benefits to the natural system as well as the society.

Consequently, the potential for the bed structures of a wind farm to act as an artificial reef may be highlighted as a possible benefit to the marine environment and must be considered, especially in terms of the additional stress and disturbance on the new and stable ecological system due to a complete decommissioning. During decommissioning, it will be necessary to achieve a balance between international obligations to ensure safety of navigation and to protect and preserve the created ecosystem within the marine environment (Smyth, 2015).

In the US states of America, the Gulf of Mexico and a small number of other locations (e.g. Brunei), the Rigs-to-Reefs programme allows a potential option for leaving part of the underwater structure either in-situ or towed to an approved location. However such strategies are a matter of debate primarily on environmental grounds and also through the obstructions caused. In the early days of North Sea oil and gas decommissioning in the 1990's, towing to a deeper location was the intended disposal method for the Brent Spar floating storage unit, after decontamination. However, opposition led to the unit being brought to shore for disposal and this policy has become adopted.

2 Research Theory and Methodology

2.1 Available market knowledge

In March 2017, DONG Energy (today Ørsted) had the responsibility of performing the decommissioning of the offshore wind farm, Vindeby, in the south-east of Denmark. This park was constructed in 1991 and consisted of eleven 450kW OWT. The blades, nacelle and towers were taken down as a reverse installation by a jack-up vessel. The foundational structures at this farm were concrete gravity-based and were broken down on site by hydraulic demolition shears. The 40m tower and 30m blade length of this old farm are relatively small compared to sizes nowadays. This wind farm has been used as a pilot in many decommissioning studies in the years after.

A few offshore wind farms have been decommissioned also in UK, however, most experience on removing offshore installations come from the large numbers of the early oil and gas installations which have been removed over the last twenty years. In Europe, the oil spill prevention, administration, response (OSPAR) regulations dominate and worldwide the international maritime organisation (IMO) regulations hold. Both sets of regulations stipulate the complete removal as the default expectation with some exemptions considered on a case-by-case basis. The main exemptions (or derogations) that are relevant to both oil and gas and offshore wind concern components on the sea-bed or embedded in the sea-bed, on the basis that the environmental damage and cost of complete removal would be excessive. Thus, it is generally permitted that piles are cut just below sea-bed level; that rock protection is left in-situ; and, though more debatable, that cables and buried pipes may be left in place if the risks of becoming exposed are low.

As already outlined, other derogations have resulted in some gravity base foundations being left in place after removing sufficient upper structure to allow 55 m draft for shipping: such derogations were allowed for foundations where complete removal was not sufficiently considered during their design and installation. More recently-designed gravity base structures are intended to be released from the sea-bed and ballast removed to allow them to be re-floated and towed to shore and it is expected that any future gravity-based foundations will need to be designed for complete removal.

The decommissioning of oil and gas structures is already a large industry in itself, with an extensive body of knowledge and literature available. For example, reports and guidance have been issued by the International Association of Oil and Gas Producers (OGP, 2012), the UK Government (UK_Government, 2011) and the industry body Oil & Gas UK (Oil&Gas_UK, 2012).

Focussing on an assumption of onshore disposal, the main processes involved in decommissioning an oil and gas installations are (DNV_GL, 2016):

- Preparation and cleaning of the tanks and processing equipment, disposal of hydrocarbons, removal of loose equipment, strengthening of steelwork and lifting points

- Plugging and abandonment ; sealing the borehole and inserting a temporary or permanent plug depending whether reactivation of the flow needs to be possible in future
- Removal of topside structures, either in pieces or in a single lift. Requires separating at the joints between platform and foundation. Finally, transport to shore.
- Removal of foundation – either in pieces or in a single lift. Piles are cut underwater at 2 to 5m below seabed level. Concrete foundations are de-ballasted and floated, or lifted; or cut underwater into sections that can be handled. Removed components are transported to shore.
- Decommissioning of pipelines, cables and seabed structures; usually left in-situ unless they interfere with navigation or fishing.
- Site clearance; removal of debris and loose materials from seabed.
- Onshore dismantling, disposal and recycling in specialised facilities where leaks can be contained.

The oil and gas industry technologies have many similarities with offshore wind and will be the guiding factor when a lot of new companies will enter the offshore wind decommissioning industry. The installations are built to survive and operate in the open sea, and employ a similar range of support structure. Moreover, the range of vessels used, from survey vessels, jack-ups and crane vessels to support vessels is also comparable.

On the other hand, although experience from the oil and gas industry may be useful, care should be exercised when transferring to the offshore wind industry. Main differences between offshore wind and oil and gas technologies result from (DNV_GL, 2016):

- Water depths are higher in oil and gas installations.
- Offshore wind installations are generally closer to shore.
- The installations in offshore wind are almost identical if different wind farms are compared. In oil and gas, the platforms are unique and complex structures. The methods of construction, maintenance and decommissioning are strongly influenced by the logistics.
- The weight of an offshore wind turbine including the tower is typically around 750 t for a 6MW model, whereas it can reach up to 3,000 tonnes for the substation topsides. The topside of an oil platform may weigh 10,000 tonnes or more. The monopile foundations used for wind turbines can exceed 7 m diameter whereas any steel piles for oil and gas structures do not exceed 3 m diameter since the distributed load lends itself better to multiple piles.
- Offshore wind installations are generally "clean" containing small quantities of fluids which are readily removed, whereas oil & gas structures are often contaminated by hydrocarbon residues as many members are used for storage of oil, drillings and waste lubricant.
- Oil & gas decommissioning works exercise higher health, safety and environmental standards as incidents could possibly lead to adverse environmental impact. Therefore, oil and gas decommissioning works involve more accurate operations.

Table 1 Decommissioned offshore wind farms (4c_offshore, 2019)

Country	Wind farm	Capacity	Operational years	Year Decommissioned	Foundation type
Denmark	Vindeby	4.95 MW	26	2017	Gravity-based
Germany	Hooksiel	5 MW	9	2016	Tri-pile
Netherlands	Lely	2 MW	23	2016	Monopile
Sweden	Utgrunden I	10.5 MW	19	2018	Monopile

	Yttre Stengrund	10 MW	15	2015	Monopile
UK	Blyth	4 MW	13	2019	Monopile
	Beatrice Demonstration	10 MW	8	2016	Jacket (piled)

The list of the decommissioned wind farms up to 2020 in Table 1, which are all in Europe, shows that in total approximately 50MW of offshore wind power has been decommissioned. If this number is compared to the total amount of installed offshore wind capacity which equals to 35GW in 2020, then it can be concluded that decommissioning of wind farms will be one of the main focus of the industry during coming decade and will run in parallel with the commissioning of new offshore wind farms.

2.2 Regulatory framework

2.2.1 Worldwide

The decommissioning process for the whole offshore industry is currently insufficiently regulated and lacks relevant guidelines for recommended practices. This problem is not unique for the offshore wind industry but does also affect other sectors, such as the oil and gas. Additionally, the limited current available practices are mainly based on oil and gas offshore projects and often do not apply to renewable energy projects and specifically, offshore wind farms.

A first overview of the regulations concerning the decommissioning of offshore wind farms was developed in (Januario, Semino, & Bell, 2007). The importance of guideline elaboration as part of the European Maritime Policy was highlighted. Additionally, it was firstly recommended to totally remove any offshore installation, unless there are strong reasons not to do so.

Nonetheless, in most cases, as explained in (Topham & McMillan, 2017), the detailed decommissioning programmes are found to be rather simplistic and the costs underestimated. Both aspects may lead to lower rates of return and to non-sustainable decommissioning solutions which increase the owner's liability. Additionally, no prescription is indicated on what needs to be removed; the decision between partial or total removal would be made based only on economic reasons.

Apart from limited existing regulations, the polluter pays' principle is the only strong guiding principle, where any damage done to the environment has to be remediated by the owner. Thus, the elaboration of specific guidelines is strongly recommended including precise liabilities for the owners (Topham E. , 2019).

The existing regulatory standards, guidelines and best practices for offshore wind farm decommissioning are based on existing standards from the maritime conventions and other industries such as oil and gas. These include the following:

- Convention on the prevention of marine pollution by dumping of wastes and other matter (London Convention) (1972);
- The United Nations Convention on the Law of the Sea (UNCLOS) (the United Nations 1982);
- Best practicable environmental option (1988);
- International Maritime Organisation (IMO) guidelines and standards for the removal of offshore installations and structures on the continental shelf and in the exclusive economic zone (1989);

- Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention 1992);
- Review of the Current State of Knowledge on the Environmental Impacts of the Location Operation and Removal/Disposal of Offshore Wind-Farms (OSPAR Commission 2006);
- OSPAR Guidance on Environmental Considerations for Offshore Wind Farm Development (2008).

Some European standards and best practices can be found in:

- Environmental impact assessment directive (85/ 337/EEC)
- Habitats directive (92/43/EEC)

2.2.2 Netherlands

Decommissioning regulations in the Netherlands to date have been set under the 'Wet Beheer Rijkswaterstaatwerken' (Water Control Act, part of the 'Waterwet'; the Water Act)], although these may be changed as part of the ongoing amendments to the offshore wind regulatory landscape in the country.

The existing regulation requires removal of the installation after asset's operation as to "not hinder other use or disrupt the environment". This can be translated to the removal of the wind turbines and the foundations (monopiles) up to 6 m below the seabed (however this may change by the time the decommissioning is actually required). Decommissioning of any onshore works is normally described in the building permit delivered by the relevant local authorities. Developers have to provide reasonable financial security, by bank guarantee before construction permit can be obtained. In most cases the developer makes an estimation which is then considered by the competent authority as part of the general approval process (DNV_GL, 2016).

Regulation on offshore decommissioning in the Netherlands states that the cables used to connect them to the onshore grid have to be removed once they are not in use anymore. This also applies for other materials that ended up in the area of the OWF during construction, exploitation or decommissioning. All this is regulated in the Water Act, however, under specific circumstances, it is possible to obtain permission from the responsible minister to leave the installation of cable in place. Moreover, the minister can decide that the export cable has to be left in place if its removal would lead to "damage to the marine environment or to other rightful usages of the sea".

A generic decommissioning plan needs to be attached to the construction permit request which needs to be approved by the relevant authorities several months in advance of the actual works. The decommissioning works follow then a detailed removal plan which the project developer drafts at least four weeks before the start of the removal phase. Once the offshore wind farm or cable is removed, this has to be notified to the responsible minister (Kruse, 2019).

Specific requirements for the decommissioning of the wind farm are also set in (RVO, Borssele Wind Farm Zone I and II Appendix B: Summary Environmental Impact Assessment Part of Project and Site Description, 2016) by the Netherlands Enterprise Agency during the tender phase of the project. The permit holder is obliged to dismantle and remove all elements of the wind farm within two years, but always within the term of validity of the permit. Additionally, the permit holder will guarantee the removal of the wind farm by means of a bank guarantee for the State in the amount of €120,000 per MW installed. This amount is annually increased by 2% as a result of indexation.

Developers are typically small companies, unable to provide a bank guarantee for 20 years. Recently the Government has decided that developers of wind farms must make payments for a minimum of 10 years into a separate fund from the start of the farm construction. The Government has access to this fund in the event of insolvency of the owner/operator (Januario, Semino, & Bell, 2007). (RVO, Borssele Wind Farm Zone I and II Project and Site Description, 2016)The terms and conditions of the above requirements are further described in the Wind Farm Site Decisions (WFSD's) which are site specific conditions for building, operating, maintenance and decommissioning wind farms.

2.2.3 United Kingdom

One of the countries with the most experience in decommissioning of offshore installations is the United Kingdom. The last practical decommissioning projects of offshore wind farms in the UK were the 80MW site North Hoyle in 2004 and the two-turbine 4MW site Blyth in 2000. Nevertheless, decommissioning activities in the UK are limited mostly to oil and gas installations as well as pipelines. These are regulated through the Petroleum Act 1998 which covers the United Kingdom continental shelf (UKCS). Owners of oil and gas installations and pipelines are required to decommission their offshore infrastructure at the end of an oil field's lifecycle. The measures to decommission installations and pipelines are to be discussed in decommissioning programs listing all items of equipment, infrastructure and materials that were installed or drilled together with a description of decommissioning solutions for each (Kruse, 2019)**.**

The United Kingdom was one of the first countries to develop some regulatory guidelines for offshore installations related to the production of energy:

- Decommissioning offshore renewable energy installations (Department of Trade and Industry 2006);
- Decommissioning topic strategy (Health and Safety Executive (HSE) 2001).
- Decommissioning offshore concrete platforms (Health and Safety Executive (HSE) 2003).
- Energy Act 2004 and amendments made in Energy Act 2008
- Department of Energy and Climate Change (DECC) Guidance Note: "Decommissioning of offshore renewables energy installations under the Energy Act 2004"

The last Guidance Note is based on the decommissioning provisions in the Energy Act 2004 and applies to installations that are used for purposes connected to the production of energy from water or wind. Additionally, they shall permanently rest on (or attached to) the seabed and are not connected with dry land by a permanent structure providing access at all times. The note incorporates international obligations and summarises the range of UK legislation which is relevant to decommissioning activities, such as the Food and Environment Protection Act (FEPA) 1985 and Health and Safety legislation. As with any of the rules and guidelines, the DECC guidance may change with time. The obligations of offshore wind farm owners in the UK regarding the decommissioning of the installations are also contained the same Guidance Note. From these regulations, a decommissioning programme is required in the UK from developers to gain their construction permit which is applicable for other countries too. This plan includes a description of the decommissioning operations that would need to take place at the end of the wind farm lifetime, together with their cost implications.

The Crown Estate owns much of the seabed in UK waters and has rights to provide exclusive rights of the seabed to developers. The UK Government and The Crown Estate work together to avoid duplication with developers only required to submit one decommissioning plan, one financial security with no additional provisions provided by the Crown Estate (DNV_GL, 2016).

2.3 Literature review and research questions

The literature on decommissioning of offshore wind farm structures is limited but it exists. One of the pioneers is Eva Topham who has made several publications related to this topic. Subjects of her research was the challenges that the decommissioning of wind farm might face (Topham E. , 2019), where she explores the state of the knowledge regarding the decommissioning process of offshore wind farms and emphasizes how much this process is affected by high uncertainties related to the regulations, the planning of the process, the vessels' availability and the environmental impacts.

Another topic of her research is sustainable ways of decommissioning wind farms (Topham & McMillan, 2017), which explores ways that the decommissioning processes may become faster and most effective and how the budget estimations may be improved. Several publications try to evaluate the regulatory framework in specific countries perform gap analysis such as in (Januario, Semino, & Bell, 2007).

Additionally, several research institutes in collaboration with companies (TNO, 2020), (DNV_GL, 2016) performed studies related to offshore wind decommissioning. DNV's study focus was to design likely scenarios for offshore wind decommissioning in Ontario's fresh water lakes and create a cost model for these works. It was performed in collaboration with Ontario Ministry of the Environment and Climate Change. TNO's study aim is to identify the preconditions under which business developments related to the decommissioning of offshore wind farms (including the reuse of materials from offshore wind farms) for South Holland and the Rotterdam port area can be realised. These should result in initial recommendations for further steps towards a roadmap for an ecosystem for decommissioning in South Holland. The study was sponsored by Port of Rotterdam, Gemeente Rotterdam, TUDelft and others. These studies show that a big market will be created in the coming years and private and public organisations are interested in strengthening their positions to be better prepared in future evolution.

Finally, from the early realisation of offshore wind farms, special attention was paid to the disposal options of the materials used. This is common for all types of power plants to evaluate more accurately the environmental impact. A study performed by Interreg for the North Sea region on behalf of European Union presents the recycling options and rates of the materials used. Additionally, tries to assess the climate impact of offshore wind projects

The main questions which this study tries to answer is a combination of new research hypotheses and optimisation of hypotheses which have been partly answered before in the literature and are presented below:

- How necessary it is to look into de-commissioning of offshore wind farms?
- What is the available market knowledge about de-commissioning bulky offshore structures?
- What is the most effective method of decommissioning Borssele 1+2?
- What assumptions have to be made and how will these assumptions be verified in the future?
- What can be the composition of a project team for this assignment?
- What would be the roles and responsibilities of the team members?

- What would be the most efficient and effective management structure for the project design and the operations?
- How could the budget be optimised?
- What would be an indicative budget estimation for the de-commissioning engineering and operations?

Answers to these questions will help the project developers to make a more accurate ABEX estimation which will reduce the bank guarantees necessary during the permit application process. Additionally, they can be better prepared and organised on the personnel and resources requirements to commence the decommissioning works. Finally, the most state of the art techniques are discussed to optimise the project management processes.

2.4 Description and justification of the research methodology

The main research methodology will be documentary analysis which shall involve collecting and analysing data from the existing documentation on the topic. Given that literature on offshore wind decommissioning is limited, data shall be analysed from relevant different sectors such as offshore structures for oil the gas industry. Several publications are made about the technical description of the decommissioning methods. This has helped the author to evaluate the different methods and use the most technically proven and cost efficient way of decommissioning an offshore wind farm. The Open University of Cyprus e-library has been used to gain access to several publications and journal articles.

Several technical options for decommissioning methods have been investigated by accessing supplier's material and in several cases contacting the supplier. Additionally, the Borssele 1+2 project description reports by The Netherlands Enterprise Agency have been used. The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO) is an executive body of the Dutch Ministry of Economic Affairs and Climate Policy (Ministerie van Economische Zaken en Klimaat, EZK). Additionally, is responsible for the collection of the site data which provide information for FEED studies and make competitive bids in the permit tenders possible.

To answer all the research questions interviews were performed with industry experts to gain further in-depth insight into the specifics of the topic. The following persons have been interviewed:

L. B. J. Decommissioning Project Manager Vindeby Ørsted

L. was the project manager of Ørsted responsible for the decommissioning of their first offshore wind farm Vindeby in 2017. Several emails have been exchanged and meetings have taken place where Lars as a pioneer in this industry tried to transfer his experiences and his lessons learned on a technical and managerial level of such a demanding operation.

C. D. D. Asset Manager Borssele 1+2 Ørsted

C. is the Asset Manager of Borssele 1+2 wind farm. She ensures that the life time profitability of the windfarm is optimised, through developing asset strategies, balancing cost, production and risk and monitoring performance. She was also part of the permit application team for Borssele 1+2 and several other wind farms of Ørsted. Celine could share her experiences for applying for a permit for a wind farm in the Netherlands especially, with regards to the decommissioning requirements.

D. E. C. Cost Estimator for offshore projects Boskalis

D. has worked several years as Cost Estimator and Tender Engineer preparing bids for offshore wind projects. She was able to provide some ballpark figures for the offshore rates of vessels and personnel. Additionally, her input was significant on estimating the duration of the different activities.

Lastly, own experience is used in essential parts of the analysis since the author is working in the offshore wind industry for more than ten years.

The main contribution of this assignment is its external validity. The findings can be generalised to all countries where offshore wind has been implemented. The methods used are the most common for this industry and the model developed can be adjusted to any situation/country only by adjusting the input parameters such as duration of works, rates etc..

3 Presentation and analysis of the research data

3.1 Project description

The Borssele 1+2 windfarm is located 22 km off the coast of Zeeland province, the Netherlands and was built in 2020 by Ørsted, the leader in offshore wind capacity installed worldwide. The permit lifetime in the Wind Farm Site Decisions amounts to 30 years. As this includes construction and decommissioning there is roughly 25 years left for operations.

Ørsted will manage the decommissioning process. A draft decommissioning plan was prepared when obtaining the construction permit. A detailed one will be prepared and assessed at a later stage and in agreement with the competent authority. This plan will outline the methods and considerations which will be adhered to when disassembling the wind farm. The decommissioning plan will consider the most suitable technology available and any relevant environmental requirements and take into account the relevant legislation at the time of decommissioning. The current assignment's main goal is to facilitate the preparation of the detailed decommissioning plan and to provide an as accurate as possible ABEX calculation. This calculation may be used to re-negotiate the bank guarantees, agreed in the beginning of the project, which can save enormous costs for the developer.

The Borssele 1+2 windfarm has a total capacity of 752MW and consists of 94 Siemens-Gamesa Renewable Energy (SGRE) 8MW wind turbines (WTG) with a rotor diameter of 167 meter.

Monopiles (MP) with 8.3m diameter in combination with a transition piece (TP) have been selected as the preferred support structure to carry the WTG both from an economical and installation perspective. The MPs are designed individually for each system and their specifications are shown in Table 2. One layer scour protection has been installed around the MPs. The fabrication was executed by experienced suppliers; EEW SPC and SIF for the Monopiles and Bladt and EEW OSB for the TPs.

Table 2 Borssele 1+2 MP and TP dimensions

Foundation type	Weight (T)	Length (m)	Penetration (m)
TP	375	22.5	-
MP max	1170	76	33.1
MP min	560	47.5	23.5
MP average	849	63.6	28

The WTG are connected to the offshore substation via a network of inter-array cables which are laid between them and the offshore substation. The cable type used is an armoured three-core copper subsea cable. 94 cables, in total, 170 kilometres with two different cross sections have been laid in the wind farm. The average weight of the cables is 24kg/m. The supplier for the array cable and termination works is NEXANS GmbH and for the cable protection system (CPS) is Tekmar Energy. The CPS system mounts the cable to the entry hole of the J-tube in the TPs and the substation, as shown in Figure 9. The type used is the de-latching which means that it can be recovered without diver intervention.

Figure 9 Tekmar CPS system connected to a J-tube

On the offshore substation's cable deck, the subsea array cables are stripped and the single core cables are directly routed to the 66 kV switchgear owned and operated by the transmission system operator (TSO), Tennet. In the wind turbine end of the array cables, the subsea array cables are terminated directly to the combined 66 kV wind turbine switchgear which is located in the foundation (TP). The wind farm layout is presented in Figure 10. Extending an area over 128.3km², the Borssele 1+2 windfarm is located in water depths ranging between 14m and 38m.

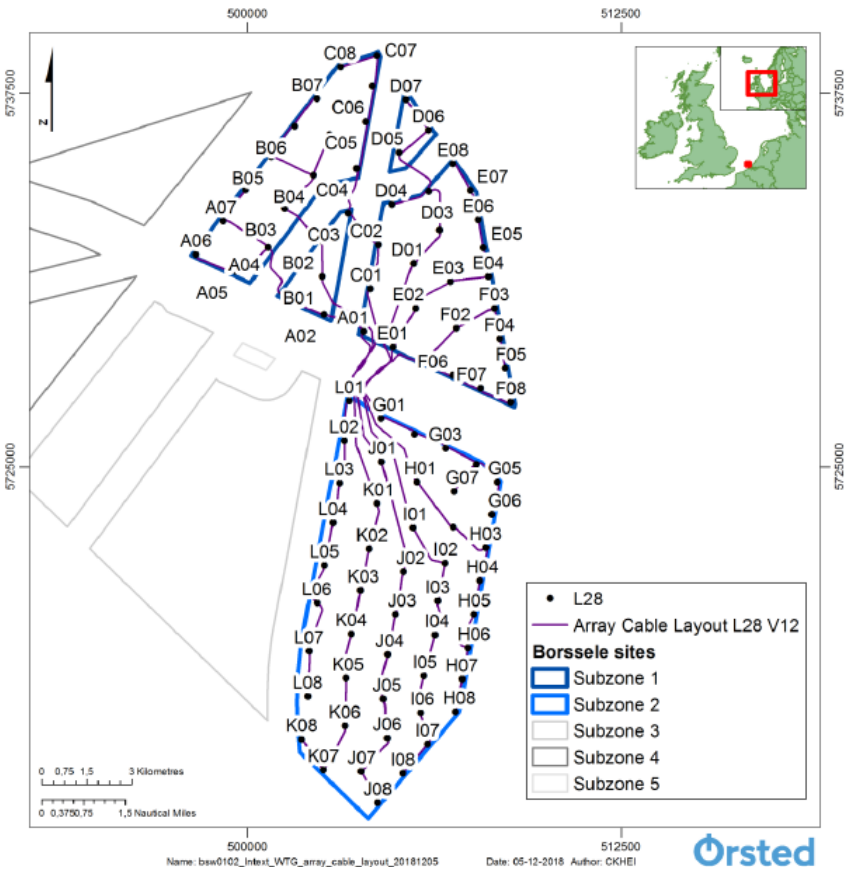


Figure 10 Borssele I & II wind farm layout

3.2 Environmental Impact assessment

A description of the site, surroundings and characteristics of the site together with all data collected by the Nethelands Enterprise Agency regarding the physical environment are included in (RVO, Borssele Wind Farm Zone I and II Project and Site Description, 2016).

The Borssele 1+2 zone is located at the southern border of the Netherlands Exclusive Economic Zone (EEZ); 0.5 km from the Belgium EEZ. The zone borders a sand extraction area in the southeast and a piloting area in the east. Anchoring areas and a shipping corridor are located at the north side of the zone. The Belgian dedicated offshore wind zone is located directly to the southwest.

Borssele 1+2 zone does not have cables or pipelines crossing this site; it consists of one parcel with an effective area of 63.5 km2 . A summary of all the studies and measuring campaigns which were performed before the tender phase commenced is published in (RVO, Borssele Wind Farm Zone I and II Project and Site Description, 2016) and is covering the following:

- Morphodynamical characteristics
- Archaeological assessment
- UXO risk assessment
- Geophysical survey
- Geotechnical survey
- Meteorological and meteocean data

3.2.1 Morphodynamical characteristics

A geophysical survey was performed in June 2015 and provided high resolution data and eventually an in-depth insight into the seabed morphodynamics at the site. The site is characterised as highly dynamic, consisting of static, shore-parallel sand banks overlaid with dynamic shore-perpendicular sand waves.

3.2.2 Archaeological assessment

No early prehistoric sites have been identified within the Borssele 1+2 zone and the likelihood of encountering prehistoric archaeology within the zone is small. Therefore, further archaeological surveys regarding the prehistoric sites were not recommended during the tender phase of the project.

However, historic shipwrecks have been identified in the area and shipwrecks of high archaeological significance have been found in the vicinity, leading to an average chance of encountering historic archaeology. Since no historic objects were found during the construction of the wind farm, the probability to find some during the decommissioning works, where the operations are limited, is minimised.

3.2.3 UXO risk assessment

Unexploded Ordnances (UXO) from both world wars are likely to be present at the Borssele 1+2 site, which is therefore considered an UXO risk area. With proper UXO risk management, the risks can be minimised. Due to the highly dynamic soil morphology, Ørsted conducted UXO search and removal operations immediately prior to construction activities. Therefore, similar operations during the decommissioning of the wind farm are not required.

3.2.4 Geophysical survey

The surveys which were conducted by the Netherlands Enterprise Agency have provided:

- Accurate bathymetric charts of the development areas
- Information on seabed features including:
  - natural objects such as boulders
  - non-natural objects such as wrecks, debris or UXOs
  - geological formation to help identify locations of structural complexities or geohazards such as accumulations of shallow gas, buried channels
- The position of existing cables and pipelines
- Input into the specification and scope for a geotechnical sampling and testing programme following the completion of the geophysical survey
- A comprehensive interpretative report on the survey results obtained to assist design of the offshore foundations/structures and cable burial.

The above surveys can be used for the decommissioning operations because the seabed geophysics will not be modified in a time span of 25-30 years. Additionally, a geophysical survey will be performed after the decommissioning activities are completed. Its results can be compared with the same study performed before the construction of the wind farm to evaluate the impact to the seabed soil.

3.2.5 Geotechnical survey

The geotechnical reports include information about:

- Geotechnical logs for borehole locations
- Interpretation of soil profile.
- Selected results of laboratory tests such as: Piezo and Seismic CPT and Pore Pressure
- Cone resistance (net/total), sleeve friction, pore pressure, friction ratio and pore pressure ratio
- Recorded shear waves (X and Y) and derived shear wave velocity.
- Dissipation Tests, i.e. cone resistance and pore pressure versus time

3.2.6 Meteorological and Metocean data

Fugro OCEANOR has placed two metocean buoys in the Borssele 1+2 site in June 2015, which provide meteorological and oceanographic data. Monthly results are being made available at the Netherlands Enterprise Agency. The decommissioning of these buoys is outside the scope of this study.

Finally, possible mitigating measures to impact the environment were suggested by RVO investigation (RVO, Borssele Wind Farm Zone I and II Appendix B: Summary Environmental Impact Assessment Part of Project and Site Description, 2016) and are to be respected also during decommissioning.

The environmental aspects which have been considered are the birds and bats, marine mammals, shipping and safety and other use functions such as fishery. The operations have to stand still in certain weather conditions in combination with identified migration of birds and bats to avoid any collision or disturbance. To avoid disturbance of marine mammals, the decommissioning period has to be reduced as much as possible. “Slow start” and “Acoustic Deterrent Devices (ADDs)” have to be used, while the maximum permissible sound level has to be respected (160dB at 750 metres distance).

Automatic Identification System (AIS) has to be used by all vessels and wind turbines in the Borssele 1+2 decommissioning site to prevent any disturbance to shipping. Finally, a corridor is opened up inside the wind farm’s boundaries to limit the sailing time to fishing grounds and other destinations.

3.3 Scope of work

In broad terms, decommissioning will involve the removal of non-buried infrastructure (e.g. wind turbines), while buried components (e.g. monopiles and cables) may be left in situ or removed depending upon regulatory requirements at the time of decommissioning. Advances in technology may also allow consideration of alternative decommissioning measures. For the basis of cost estimate, the following decommissioning activities are considered:

3.3.1 Wind Turbine Generators

The dismantling and removal of WTG components (blades, nacelle, tower etc.) will largely be a reversal of the installation process and subject to the same constraints. However, potentially less precision and care is needed as the structure has served its purpose. Using today's technology, dismantling of the turbines will require a jack-up vessel to ensure adequate control and to cope with the relatively high lifts and high crane hook loads. Even though decommissioning may not require the same level of precision and care as during installation, it will be undertaken in the same controlled manner and in accordance with a risk management plan to ensure the same or higher level of safety. Although some parts could be handled more roughly during decommissioning, due to the possibility of bolts and other fasteners being seized over time, it is expected that the reversal of the installation process for the WTGs will be approximately the same time as the installation phase at the beginning of the projects life.

Figure 11 Installation of a wind turbine in Borssele 1+2

Before the task can begin, several months in advance it will be necessary to secure a suitable jack up vessel. It must be noted that the most suitable vessels are not usually available at short notice. Therefore, the longer planning period for this work will assist to an optimal procurement and invitation to tender (ITT). The most important items to be included in the jack up vessel design during tendering are;

- Crane capacity and reach
- Number of components to carry per trip based on the provided dimensions and weights
- Jack up leg length and expected maximum leg penetration

- Accommodation for client supplied personnel and representation
- Deck area, draft deck layout including position of all lifting tools
- Stability calculations

The jack up locations coordinates used during the construction of the wind farm can used also during the decommissioning works.

Besides securing the suitable jack-up vessel to perform the task, required special purpose lifting appliances (yokes, brackets, turning gears, yaw-boxes), shall be procured and re-certified as required. Timely training of personnel to operate the lifting appliance and perform lifting operations in a safe and professional manner shall not be underestimated.

The general methodology for carrying out wind turbine decommissioning will be:

- De-energise the wind turbines and isolate them from the grid
- Disconnect power cables and related control and communication cables at the nacelle and tower base in preparation for offshore dismantling. These activities can be performed several weeks in advance by Ørsted authorised persons
- Mobilise suitable heavy lift vessels to site
- Prepare decommissioning teams, ensure all personnel are adequately trained and competent to carry out assigned tasks. Ensure personnel are familiar with working procedures, established safety management system and scope of work
- Position the jack-up vessel close to the turbine position, pre-load and jack up to working height. Once the vessel is elevated, attach gangway to the TP and external power supply to the TP and WTG
- Technicians enter the WTG, complete safety checks and prepare for lifting
- Prepare lifting tools, sea-fastening, bolts, slings, tag lines etc.
- Prepare the crane and hand it over to the lifting team.
- Install portable turning gear, yaw-box, etc. (if required).
- Check that the nacelle systems required for dismantling are operational on temporary power supply
- Spin the hub to bring the first blade in required horizontal position
- Remove rotor blades one-by-one and lower to blade storage rack
- Remove nacelle and sea-fastening
- Remove tower either in one piece
- Vertical or horizontal stowage of the towers on the vessel shall be planned in advance.
- The turbine parts will be placed into engineered and procured sea-fastening approved by the marine warranty surveyor (MWS) on the vessel and transported to the selected harbour. The MWS is the representative of the insurance company who needs to evaluate and approve all works/equipment
- Offload the components/parts by the jack-up main crane to optimise the programme
- Parts will be processed for reuse, recycle or disposal

Once onshore, components are likely to be processed as follows:

- All hazardous substances and fluids will be removed from the wind turbines (such as oil reservoirs and any hazardous materials and components). All such materials will then be disposed of in accordance with relevant regulations at the time of disposal
- All steel components will be sold for scrap to be recycled. This forms the bulk of the wind turbine structures
- At the time of decommissioning all options for the recycling of the wind turbine blades (fibreglass) will be considered. Recycling or disposal, if required, will be carried out in accordance with the relevant regulations in force at the time of decommissioning

The decommissioning of the wind turbines will require the following:

- Electrical authorised persons to secure isolation from the grid and cable jointers to disconnect the cables
- Jack-up vessel to cope with the relatively high lifts and high crane loads. The costs for the vessel include the complete crew
- Rigger team for carrying out the manual work
- Team of specialists such as lifting supervisor, client rep. etc.
- Harbour lease for the decommissioning vessel
- Sea fastening for the items that the vessel is going to transport to harbour
- Harbour fees, pilotage etc.
- Cost for equipment and people in harbour

The jack-up vessel selected for the decommissioning of the WTGs is a DP2 offshore installation vessel with a crane capacity of 900T at 24 metres. It has a free deck area of 3350m2 and a max pay load of 6000 Tonnes. It can carry easily 4 WTG Nacelles, 4 towers and 12 blades.

3.3.2 WTG Foundations; Monopiles and Transition Pieces

The MPs and the TPs are removed using the same vessel, so that the decommissioning vessel only has to go to one position only one time. For decommissioning of monopile foundations, the MP will first be cut below the TP. The TP will then be lifted and secured to the jack up vessel. Subsequently, the monopile will be cut below the seabed level to a depth that will ensure the remaining foundation is unlikely to become exposed. This is likely to be approximately one meter below seabed although the exact depth will depend upon the sea-bed conditions and site characteristics at the time of decommissioning. The goal is the environmental impact is minimised and the process becomes more sustainable.

The methods of cutting monopiles available in the market are high pressure water jetting of diamond wire cutting. For both methods, extra project specific cutting equipment needs to be rented. An alternative is cutting by use of explosives, however, although it is cheaper, it is considered environmentally unfriendly and is rejected. The cutting method selected needs to be according to the legislation at the time of decommissioning. Diamond wire will be the preferred tool for the cutting operations as it is the least environmental harmful, can work in a wider range of monopile diameters and it is relatively economical.

The sequence for removal of a monopile foundation and a transition piece is anticipated to be:

- Mobilize suitable vessel (jack-up or heavy-lift vessel)

- Deploy ROVs to inspect the foundation and reinstate lifting attachment if required
- Cut the monopile approximately 1m below TP
- Lift the TP to the decommissioning vessel and sea-fasten
- Excavate with the ROV outside of monopile to approximately 0.5m below anticipated level of cutting
- Cut the monopile approximately 1m below seabed level
- Lift MP onto the decommissioning vessel. The foundation parts will be placed into engineered sea-fastening approved by the MWS on the vessel
- Transport removed foundation to the selected harbour
- All foundation parts will be unloaded to the harbour with use of the jack up vessel crane to optimise the schedule
- Removed parts will be processed for reuse, recycle or disposal

The decommissioning vessel selected for this assignment is of the same type used for removal of the WTGs. 3 MPs and 3 TPs can be transported at the same time based on the deck space and pay load.

3.3.3 Scour protection

For the scour protection removal the following options have been investigated:

- For rock armour, the individual boulders are likely to be recovered and transferred to an approved onshore site for appropriate disposal or re-use
- The filter layer is likely to be dredged and transported to be disposed of at a licensed disposal area (this could be offshore or onshore)

However, it may be agreed to leave the scour protection in-situ to preserve the marine habitat that may have established over the life of the wind farm. The actual requirements for this will be determined prior to decommissioning in consultation with relevant stakeholders and regulators. In several occasions, scour protection installed around offshore foundations or covering cables are left in situ to preserve the marine habitat which is established around them to prevent a detrimental impact on the environment, conservation aims, the safety of navigation and other uses of the sea. A typical example of an offshore construction which is converted to a reef is presented in (Smyth, 2015).

Even if the scour protection is not totally removed, it needs to be dispersed away from the cables and the monopiles to expose them as much as possible. This will be done carefully, so that the interference with the seabed is in a temporary manner. Consequently, the jack up vessel will be able to cut and remove the foundations easier with the PSV will extract the cables will less load on them.

For the dispersion of the scour protection a medium size dredger is required. Since no scour protection extraction is required, the dredger can remain on site until the completion of the works.

3.3.4 Inter array cables

The base assumption is that the offshore array cables are removed. If total removal of the offshore cables is not possible, relevant stakeholders and regulators will be consulted. In case that the stakeholders/regulators approve and the risk of the cable becoming exposed is minimal, then part of the cable may be left in situ. However, the recommendation from decommissioning experts has been to remove cables as much as possible. This is due to the fact that the time needed to remove the cable is equivalent to the time spent on burying the cable ends via ROVs.

Complete removal of the cables has additionally the benefit of leaving the site as prior to the construction of the wind farm for later use and diminishing the potential risk of cables emitting toxic substances to the ocean. Finally, there is a benefit as the scrap value of the copper cables will impact positively the business case.

As the cables can be pulled out of the seabed this leaves a minor or no mark on the seabed compared to burial of the cable ends where an appropriate hole has to be jetted. At cable or pipeline crossings the cables are likely to remain in place to avoid unnecessary risk to the integrity of the third party equipment. The cables will be cut as close as possible to the part of the cable that will not be removed. The ends will be weighted down and buried (using an ROV) to ensure that they do not interfere with the environment.

The cables will be disconnected from the foundation and the hang-off will be dismantled by authorised technicians prior to commencing the removal works. The CPS is a de-latching type one, which means that it will be removed only by pulling it out. The sequence for removal of the cables is anticipated to be:

- Identify the location of the cables that need to be removed
- Buried cables will be located using mass-flow excavation or a grapnel to lift them from the seabed. Alternatively, or in addition, it may be necessary to use an ROV to cut and/or attach a lifting attachment to the cable so that it can be recovered to the vessel
- The recovery vessel will either 'peel out' the cable as it moves backwards along the cable route whilst picking it up on the winch or cable engines, or, if the seabed is very stiff/hard it may first under-run the cable with a suspended sheave block to lift the cable from the seabed. The use of a suspended sheave block could be carried out before by a separate vessel such as a tug prior to the recovery vessel 'peeling out' the cable
- The recovery vessel chop it into lengths as it is brought on-board to store it in containers before transport to shore
- A harbour crane will be used to lift the containers from the vessel
- Cable removed will be processed for reuse, recycle or disposal

The decommissioning of the cables will require the following:

- Platform supply Vessel (PSV) with deck up to 900-1000m2 with installed equipment for cable removal and cutting
- Containers for cable storage
- Rigger team for carrying out the manual work
- ROV including 6 operators, 3 per shift
- Crane on harbour

The PSV will be equipped with chute, caterpillar for cable pulling and a cutter. The most efficient procedure is that the cable is retrieved onto the deck and cut into smaller pieces. These pieces are hereafter either placed in 40ft open containers or bundled with straps. The fixed equipment is assumed to take up 200m^2 of the deck while the remaining 700-800m^2 can be used for cable storage. Both the PSV payload and deck space govern the amount of cable that can be stored. Subsequently, the amount of cable which can be stored on the deck governs the number of trips to and from the port for the PSV.

A summary of the proposed decommissioning measures for the offshore components is outlined in Table 3.

Table 3 Summary of proposed decommissioning approach for Borssele 1+2 components

Component	Proposed Decommissioning Measure
Wind turbines	Complete removal from site
Transition pieces	Cut off 1m below the monopile and removed
Monopile foundations	Cut off 1m natural seabed and removed
Scour protection	Left *in situ*/partial disperse of scour protection at foundations and inter array cables
Cables	Complete removal

3.3.5 Logistics and Support work

During the decommissioning field work, a crew transfer vessel (CTV) will be required to provide support to the activities. The authorised technicians are transferred to the wind farm via CTVs on a daily basis. Additionally, the crew changes for vessels can be performed via this CTV which operates days and nights. This saves 1-2 working days for all vessels as transit back to the port for crew transfers is not required. The rates for crew boats is based on experience from the installation of wind farms. The number of days used in the budget for crew boats is the same as the completed decommissioning works duration. The CTV is preferred compared to an accommodation vessel because of the wind farm's distance to shore and the increased rates of accommodation vessels.

The developer owns an onshore facility which functions as mobilisation hub for the teams/CTVs, storage area and office. Therefore, these costs are excluded from the model. The facility is located at Vlissingen, The Netherlands and the distance to the wind farm is 26 nautical miles (NM). The cables scrap can also be offloaded at this facility, since the quay side and the cranes are sufficiently designed for this operation.

However, the onshore facility is not adequate to accommodate the bulky foundations and the wind turbines offloading. Therefore, an area will be rented at Sif Group, Maasvlakte to unload them temporarily, until they reach their final destination. Sif has produced part of the offshore foundations for the wind farm, and will be interested in re-buying the steel scrap. The distance from the wind farm is 38 NM. This area will be rented for the complete duration of the foundations and WTGs removal.

3.3.6 Waste management

The scale of offshore wind turbines results in a large amount of material which will need disposal once the structures are decommissioned. Many regulations across several countries prohibit the disposal of wastes in the sea and require adequate sustainable practices for disposal onshore. The waste management methods include waste handling processes adopted at the final stage of decommissioning activities where the recovered components reach the end of their lifetime. The materials handling methods include reuse, recycling and disposal/incineration.

Decommissioning industry best practice will be applied, taking into account the Dutch legislation applying at that time. Full regard will be paid towards an appropriate "waste hierarchy", which suggests that reuse should be considered first and maximised wherever possible, followed by recycling, incineration with energy recovery and lastly disposal.

Studies report that some wind turbine components such as blades are either challenging to recycle or have little salvage value. Their recyclability, therefore, requires more research compared with other components. The most practical method of waste management for blades is energy recovery through incineration (Adedipe, 2021).

An overview of expected types of wastes and their expected re-use, recycling or disposal is given in the tables below.

Table 4 Types of wastes and expected re-use of wind farm components

WTG Nacelle	Material	Re-use	Recycle	Disposal / Incineration
Transformer	Cast Iron, copper, electronics			
Drive Train	Cast Iron, steel, lubricants			
Hub	Steel			
Generator	Cast Iron, copper, electronics			
Housing of Nacelle	Steel or aluminium			
Electrical equipment	Cables, panels, converters			
Liquids / grease	E.g. fuel, oil, coolant, SF6,			
WTG Blades	Material	Re-use	Recycle	Disposal / Incineration
Bolts	Steel			
Glass fibre	Fibre composites			
WTG Tower		Re-use	Recycle	Disposal / Incineration
Tower sections	Steel			
Ladder	Aluminium			
Lift	Aluminium, electronics			
Bolts	Steel			
Cables	Copper			
Electrical equipment	Switchgear/Transformer			
Foundation	Material	Re-use	Recycle	Disposal / Incineration
Monopile	Steel			
Transition piece and secondary steel	Steel			
Scour protection	Stones			
Inter array cables		Re-use	Recycle	Disposal / Incineration
Conductor	Copper/aluminium			
Insulation material	Composite plastic			
Armouring	Steel			

Certain materials employed in the windfarm will have recycling value, Additionally, a value for scrap steel has been estimated based on approximate current values. Revenue from recycling of materials is included in the estimate of the total decommissioning costs as a revenue stream.

Table 5 Recycling revenue

WTG Nacelle	No revenue is considered within the cost model. Disposal of materials and recycling revenues from steel is expected to be cost neutral together with WTG blades.
WTG tower	Revenue is estimated based on the typical quantity of steel within the recovered portion of the WTG tower.
WTG blades	No revenue is considered within the cost model. It is assumed that the disposal of blades is cost neutral together with the WTG Nacelle and therefore not included.
MPs/TPs	Revenue is estimated based on the quantity of steel within the recovered portion of the foundation.
Array Cables	Revenue is estimated based on the quantity of copper within the recovered cables.

It is the assumption that the buyer of the scrap will do the necessary handling of the decommissioned parts onshore. Some of the recovered material has a scrap value. The only earnings included in the current cost model is the revenue for scrap steel and copper. The revenue from scrap is calculated in the decommissioning budget tool in the section "Earnings from scrap".

3.3.7 Post decommissioning

Post-decommissioning is the last phase of offshore wind farm decommissioning projects. This phase consists of all activities carried out to ensure that the site condition is returned, as much as possible, to its original state. This involves perpetual monitoring and management of the offshore wind site. During the post-decommissioning phase, the seabed soil will be allowed to settle naturally. Also, any items left-in-place (e.g. buried cable ends and pile ends) will be monitored in perpetuity. Therefore, a geophysical survey will be conducted across the windfarm site to confirm the removal of seabed infrastructure. A cost allocation, commensurate with contemporary survey costs, has been made to reflect this obligation.

3.4 Assumptions

From the past few experiences, the decommissioning process is found to be highly affected by uncertainties and many unexpected challenges. Based on the literature available, the most important challenges have been reviewed in (Topham E. , 2019) and gathered into four main aspects: the regulatory framework, the planning of the decommissioning process, the logistics and vessels' availability, and the environmental impact.

During this study, the highest priority is the safety of people involved and the environment. The safest option is selected, involving standard procedures and minimal offshore work. The minimal duration of the offshore works minimises the disruption to the legitimate users of the sea. The risk of spillage is also minimised by either removing all potential pollutants or ensuring that these pollutants are fully contained and controlled. Unnecessary dismantling will take place onshore, while, the maximum potential for re-use or recycle will be examined as mentioned before.

The current regulatory framework has been examined and it is assumed that the same framework is applicable during the time of the de-commissioning works. Sustainable development of the area is promoted by completely removing the wind turbines and the support structures. Consequently, all restrictions for the use of this area are also removed.

Specialised vessels with heavy lifting and specific stability characteristics are required for the decommissioning operations. These vessels have to adapt to the site conditions, the number of turbines, the foundation type, the water depth, the distance to the operating ports and the seabed type, as not all the vessels work under the same conditions nor have the same speed. The vessels selected in this study are fit for purpose to perform these operations as described in their specifications which will not be detailed furthermore.

The calculated costs for dismantling are based on selected current vessels and techniques including the limitations of weather conditions. The weather forecast uncertainty model used is the P50 which means: The true value is expected to be lower than the predicted value 50% of the time. This is also known as the median forecast. Cost estimates are based on the assumption that decommissioning will be conducted according to the currently available techniques, technologies and equipment. It is conceivable that future technologies will allow works to be conducted beyond what is currently possible.

Moreover, their availability can be compromised due to the forecasted demand of new offshore installations expected in the upcoming years, the operation and maintenance procedures within already operational projects, and the decommissioning of oil and gas facilities. It is assumed during the study that a proper planning allows to have vessel availability whenever this is required.

In several occasions it is known that the day rate of vessels is dependent on supply and demand. As a result, severe deviations may be observed in the ABEX calculations. However, because the developers are relatively flexible in the timing of decommissioning activities, lowest market rates can be achieved and are considered in the model. Cost estimates are based on developer's typical experience of costs at the date of issue. Future market influences may affect actual costs required at the time of decommissioning.

Synergies have not been considered but may realise further cost savings. For example, potential savings that may be available through combining decommissioning activities at more than one wind farm.

4 Findings and results

4.1 Planning, regulatory approval and remaining costs

The planning and regulatory approval costs is a large contributor to the total costs and is made up of the following:

- engineering planning base cost
- contract management
- legal permit cost
- environmental impact assessment cost
- facilities audit cost

The environmental impact assessment could be excluded because the one performed during the construction of the wind farm could still be deemed valid. The other costs will be covered by the personnel which will be hired and their responsibilities are analysed in the paragraphs below. An approach to reduce this cost is to negotiate about the most appropriate contracts with suppliers and wherever possible, in-house expertise can be used. Additionally, with increased contractor experience, there will be potential cost savings. The regulatory compliance cost is usually higher in countries where regulatory fees are required for approval and amendments. Overall, it depends on the wind farm size and regional government policies.

Some additional costs are included in the model:

- consultation for certification purposes
- contractor and vendor fees (calculated as 10% of the contract value)
- mobilisation/demobilisation of vessels is usually calculated separately to the vessels' day rate
- contractor's all risk (CAR) insurance premiums
- procurement (any tools/equipment required for the works)
- contingency planning costs

Contingency planning must be well accounted to lower the impacts of unforeseen events on the project cost. The potential risks must be identified and quantified in the cost estimates for the decommissioning project. The less the uncertainty within a decommissioning project, the less the planning and regulatory approval costs. Development of the most optimal contingency plan is a challenge, and the contingency allowance percentage is dependent on different factors such as the type of the asset to be removed, distance from shore, weather and potential breakdowns. In the current model, 10% contingency costs are added to the total sum.

4.2 Organigram: Roles and Responsibilities

A complete project organisation has to be built to cover all necessary aspects of such a demanding and uncertain task. The following roles have to be fulfilled during the preparation and execution of the decommissioning activities and have not been taken into account into any aforementioned costs. These roles can be filled in most cases by existing FTEs of the developer in most cases. If this is not possible, then contractors will be hired for short term assignments.

- Project manager
- Project engineer
- Cost controller
- Contract manager
- Document controller
- Risk manager
- Quality control manager
- Health and safety coordinator
- Facility manager/warehouse coordinator
- Offshore Decommissioning Manager

When the offshore works commence, the team will be expanded with the following roles

- Lifting supervisors
- Client Reps
- Authorised technicians

The main person responsible for the proper planning and organisation of the decommissioning activities is the project manager. One of the lessons learnt shared by the interviewees in that the complete process needs to start several years in advance because the processes are time consuming. The project manager will be the person who is responsible for the complete process from the beginning to the very end. An approximate estimation of the total duration of a big wind farm decommissioning from conceptualization to finalization is 3 years. The main responsibilities of the project manager will be to draft a decommissioning management plan, run the permit application, hire the project team, write the technical employment requirements and participate in the tender process for the contractor packages. As the project develops, his/her responsibilities could also expand to more operational aspects.

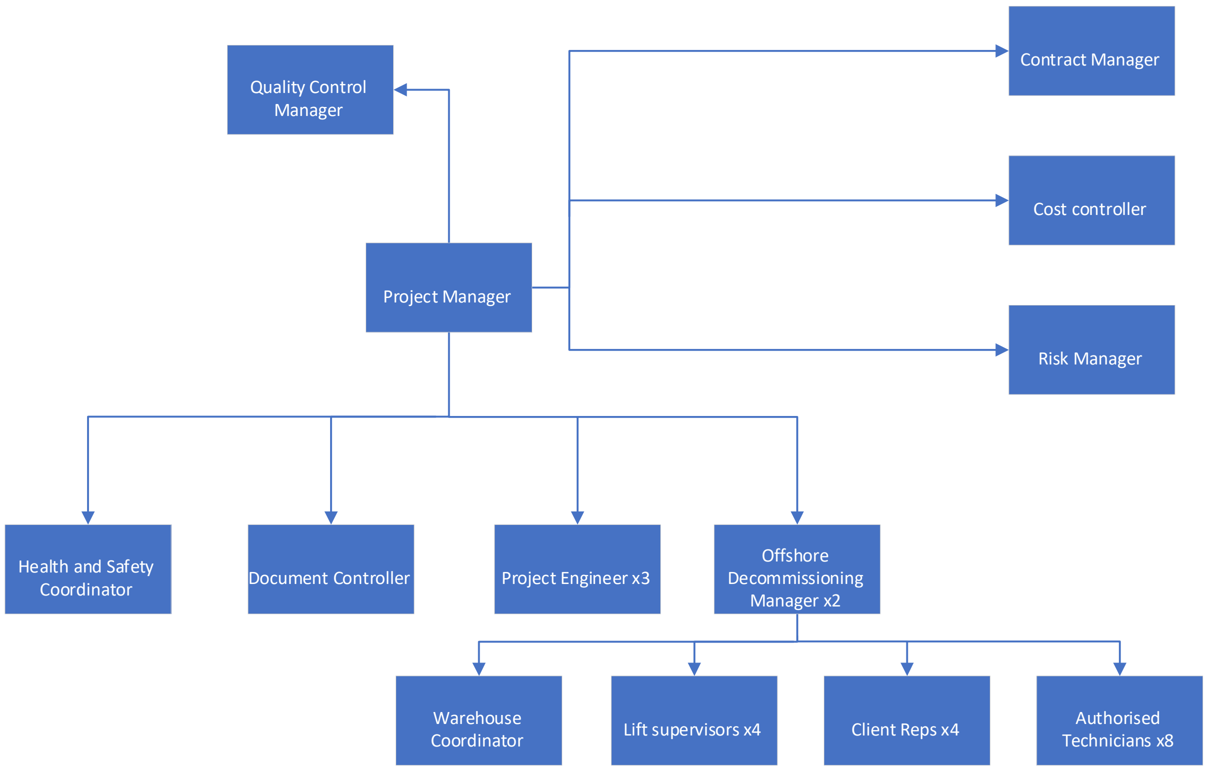


Figure 12 Organigram for a decommissioning project team

During the tender phase which is estimated to be 1 year, the project manager will be assisted partly by a contract manager (0.5 FTE) to setup the contracts and participate to the negotiations. After the first year, the workload is expected to rise for the project manager, therefore he will be assisted by three project engineers for the remaining 2 years. One of them could act also as deputy project manager. The project engineers will be focussed on specific decommissioning packages such as foundations, cables, scour protection and logistics etc... A health and safety manager is required for the last 2 years of the project. Ørsted is a project developer which pays extra attention to safety. The HSE manager will be responsible to review the safety standards of the possible contractors during the tender phase and review all method statements from a safety point of view during the planning and execution phase. He/she will also perform the HSE vessel inspections.

A risk manager will be involved partly in the project (0.5 FTE) for 1 year in the beginning of the project to assist to identify and mitigate any risks. Risk management on such an unexperienced area can be decisive on avoiding unexpected problems and eventually costs. A cost controller is needed partly for

6 months to help with the financial agreements and payments especially during the tender phase. A document controller is estimated to be needed full time for 1.5 year of engineering and operations. The main task will be the document exchange between all contractors from the tender phase until the as-built documentation and the complete archiving/hand-over.

The offshore decommissioning works are expected to last approximately 12 months. During this period two offshore decommissioning managers, will monitor the progress of the construction works and manage the offshore team. The offshore team will consist of lift supervisors who will supervise any lift operations take place offshore. The client reps will be placed in every vessel offshore, will be the first contact point between Ørsted and the contractor and will report the progress of the offshore works to the offshore decommissioning manager. The warehouse coordinator will be responsible to manage the storage building of the project and the components traffic during the decommissioning period. The authorised technicians are normally part of the high voltage team of the project. They will be responsible to isolate the wind turbines from the grid, cut the cables, dismantle the hang-offs and prepare the dismantling of the TPs and wind turbines.

A more detailed responsibilities overview of the involved persons is presented below:

Project Manager/ Project Engineer

- Run the permit application process
- Contact point for the authorities
- Develop the project plan and assign roles and responsibilities
- Hire the project team or allocate existing resources to roles
- Participate in the tender process and set up the employer requirements
- Review the contracts
- Manage any possible interfaces between third parties
- Monitor the project progress with reference to initial milestones
- Evaluate the project performance

Cost controller

- Control and monitor total project expenditure
- Allocate budget to different lots
- Benchmark offers to market prices

Contract manager

- Prepare tenders and review commercial bids
- Discuss, draft, review and negotiate the terms of the business contracts
- Act as main point of contact during the Q&A phase
- Award tenders
- Manage bank guarantees
- Manage any possible variation order requests

Document controller

- Create the document management system where all documentation will be exchanged and stored
- Setup the document requirements
- Manage the document and communication traffic to and from third parties

Risk manager

- Identify the main project risks and allocate some budget to them
- Define some mitigation actions and follow them up regularly
- Report, create indicators, update and communicate to project stakeholders

Health and safety coordinator

- Ensure that all contractors comply with health and safety standards
- Review contracts signed from a HSE perspective
- Review all method statements and risk assessments for works to be performed
- Perform all HSE vessel inspections prior to mobilisation

Facility manager/warehouse coordinator

- Manage the storage area of the project
- Control the traffic of all components
- Arrange all customs documentation

Offshore Decommissioning Manager

- Responsible for the management and coordination of the works and vessels at the offshore construction site
- Ensure project site rules and permit to work procedure requirements are established and adhered to by all personnel
- Resolve decommissioning coordination issues
- Manage the offshore team, assign tasks and control the results
- Liaise with the project manager on the progress of the works

Lifting supervisors

- Review the method statements for the heavy lifting of the equipment
- Supervise the offshore lifting works
- Report the daily progress or any incidents

Client Reps

- Maintain an accurate record of all activities on a daily basis
- Ensure that all relevant approved procedures and risk assessments are followed by the contractor
- Report and communicate with the offshore decommissioning manager

Authorised technicians

- Operate the wind turbines switchgears to prepare for cable disconnection and cut
- Release the cables from the hand-offs
- Prepare the shutdown of the wind turbines
- Ensure electrical safety throughout the decommissioning activities

4.3 Indicative project schedule

The most effective sequence of the activities is presented in Figure 13 below:

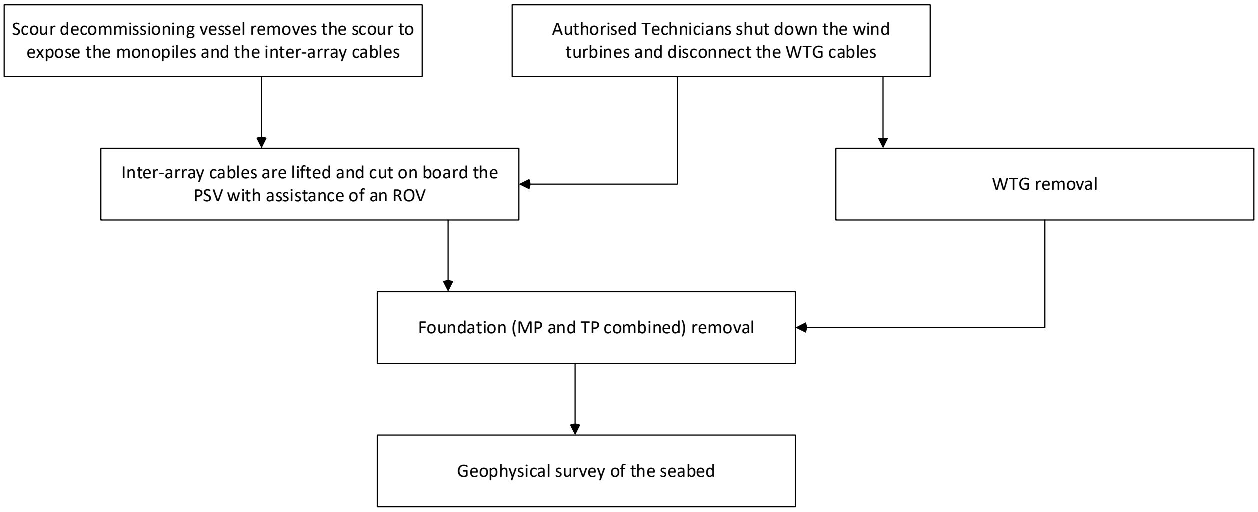


Figure 13 Offshore works sequence

The authorised technicians can work independently and start with their preparation works a couple of weeks prior the cables are removed. It is recommended that the time gap of these activities is not too long because the wind farm shall produce revenues for as long as possible. In parallel to the authorised technicians, the dredger will start dispersing the scour protection to the seabed to expose the monopiles, J-tubes and the inter-array cables.

When both of the aforementioned works are completed, the array cables including the cable protection system will be removed by the PSV with assistance of an ROV. In parallel, the WTG removal can already commence as soon as the authorised technicians have disconnected all internal cabling and shut down all systems safely.

Subsequently, when all the above are completed in some locations, the TPs and MPs removal works can begin from the jack-up vessel. Once all offshore activities are finalised, a geophysical survey will take place to evaluate the condition of the seabed.

To be able to create an indicative project schedule, an estimation of the duration of each activity is first created. The number of days which each activity will last is furthermore used in the ABEX calculation.

Table 6 Estimation of duration of scour protection decommissioning works

Activity description	Frequency	100% availability hours	Wave height restriction (m)	Average availability year P50 (%)	Total hours incl. 90% utilization
Preparion to sail	1	2	5	100	2.22
Transition to site	1	3	3	95	3.51
Dispersion of scour protection to	94	6	2	85	737.25
Relocation	94	1	3	95	109.94
Transition to port	1	3	3	95	3.51
Total number of hours					856.44
Total number of days					35.68
Total number of days including maintenance					39.65

In all calculations two factors are used:

- Time utilization factor
- Maintenance factor

The time utilisation factor equals to 0.9 and simulates all inefficiencies might be encountered in the works because of crew changes, learning curves, familiarisation with equipment and contingency. The maintenance factor equals to 0.9 and takes into account equipment failure or normal maintenance required.

The equation to calculate the total hours required for specific works is shown below:

$$Total\ hours = \frac{Frequency * 100\%\ availability\ hours * 100}{P50\ availability * utilization\ factor}$$

The number of total hours needs to be adjusted by the maintenance factor:

$$Total\ hours\ incl.maintenance = \frac{Total\ hours}{maintenance\ factor}$$

Table 7 Estimation of duration of inter-array removal works

Activity description	frequency	100% availability hours	Wave restriction m	Wind restriction (m/s)	Average Availability Year P50 (%)	Total hours including 90% utilization
Preparation to sail	8	2	5		100	17.78
Transition to site	8	3	5		100	26.67
Mass flow excavation	94	4	2		85	491.50
Positioning and retrieval	94	4	2		85	491.50
Removal of array cable	94	23	2		85	2826.14
Relocation	86	1	5		100	95.56
Transition to port	8	3	5		100	26.67
Unloading of cables	8	10		15	95	93.57
Total number of hours						4069.38
Total number of days						169.56
Total number of days including maintenance						188.40

Table 8 Estimation of duration of WTG removal works

Activity description	Freq.	100% availability hours	Wave restriction (m)	Wind restriction (m/s)	Average Availability Year P50 (%)	Total hours including 90% utilization
Preparation to sail	24	2	5		100	53.33
Transition to site	24	4	3		95	112.28
Positioning, jack up and preloading	94	4	5		100	417.78
Connection of gangway and power cable	94	1		12	85	122.88
Rigging blades	94	1		14	95	109.94
De-installation of Blade 1	94	1.5		12	85	184.31
De-installation of Blade 2	94	1.5		12	85	184.31
De-installation of Blade 3	94	1.5		12	85	184.31
De-rigging blades	94	0.5		14	95	54.97
Rigging nacelle	94	1		14	95	109.94
De-installation of nacelle	94	3		12	85	368.63
De-rigging nacelle yoke	94	0.5		14	95	54.97
Rigging tower gripper	94	0.5		14	95	54.97
De-installation of tower	94	2		12	85	245.75
De-rigging tower gripper	94	0.5		14	95	54.97
Jack down	94	1	5		100	104.44
Relocation	70	1	3		95	81.87
Preparation to transit to port	24	2	3		95	56.14
Transition to port	24	4	3		95	112.28
Arrival to port and jack up	24	3	5		100	80.00
Unloading of 1 tower	94	1.5		12	90	174.07
Unloading of 1 nacelle	94	1.5		12	90	174.07
Unloading of 3 blades	94	2		12	90	232.10
Total number of hours						3328.34
Total number of days						138.68
Total number of days including maintenance						154.09

Table 9 Estimation of duration of foundations removal works

Activity description	freq.	100% availability hours	Wave restriction (m)	Wind restriction (m/s)	Average Availability Year P50 (%)	Total hours including 90% utilization
Preparation to sail	32	2	5		100	71.11
Transition to site	32	4	3		95	149.71
Positioning, jack up and preloading	94	4	5		100	417.78
Cut MP below TP, rig, lift to deck	94	6	2		85	737.25
Preparation to cut MP 1 m below seabed	94	5	2		85	614.38

Cut MP 1 m below seabed, rigging, lift to deck and sea fastening	94	6	2		85	737.25
Jack down	94	1	5		100	104.44
Relocation	62	1	3		95	72.51
Preparation transit to port	32	2	3		95	74.85
Transition to port	32	4	3		95	149.71
Arrival to port, Jacking up and	32	3	5		100	106.67
Unloading 1 MP and 1 TP in port	94	3.5		12	90	406.17
Total hours						3641.85
Number of days						151.74
Number of days including maintenance						168.60

The duration of the offshore decommissioning activities is calculated and presented in the previous tables and leads to creating an indicative decommissioning project schedule which is depicted in Figure 14. The complete duration of the project is calculated to 40 months. 18 months is estimated to last the permitting process and 12 months the tendering phase. The offshore decommissioning works last 12 months.

Project Planner

Decommissioning schedule of Borssele 1+2 offshore wind farm

ACTIVITY	PLAN START (Month)	PLAN DURATION (Months)
Permitting and negotiations with authorities	1	18
Launch Tender for packages	12	12
Engineering for decommissioning methods	21	6
Procurement of necessary equipment	23	6
Rent onshore storage area fo MP/TP/Foundations	18	6
Preparation of WTGs by the authorised technicians	24	6
HSE inspections in vessels	29	2
Mobilisation of scour decommissioning vessel	29	1
Dispersion of scour protection arounf WTG foundations and cables	30	2
Mobilisation of WTG decommissioning vessel	30	1
Decommissioning of WTGs	31	5
Mobilisation of cable decommissioning vessel	31	1
Decommissioning cables	32	6
Mobilisation of MP/TP decommissioning vessel	32	1
Decommissioning MP/TP	33	6
Waste management	32	8
Geophysical survey at seabed	40	1

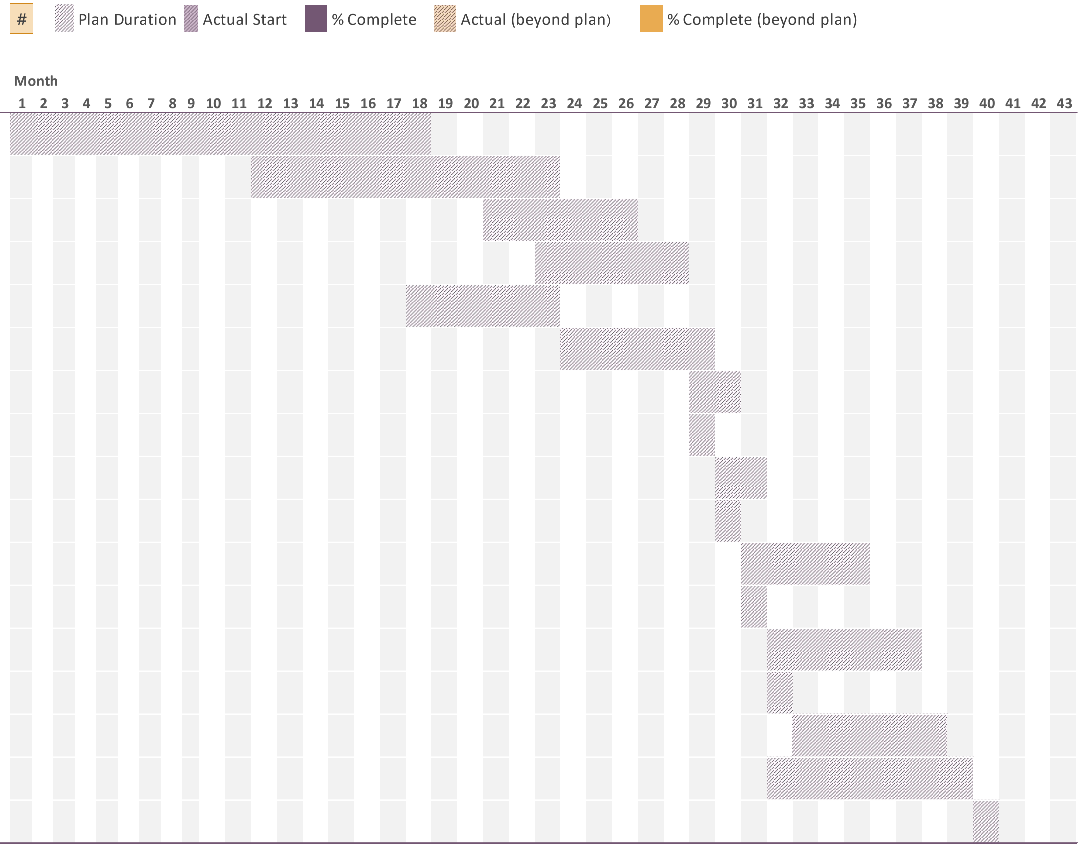


Figure 14 Decommissioning schedule

4.4 ABEX calculation

4.4.1 Rates of vessels and other activities

The vessel day rate includes all cost related to the fixed crew and are presented in Table 10. The fuel costs are calculated separately in the model.

Table 10 Vessel/offshore teams day rates

Vessel/team	Day rate (€)
Scour decommissioning medium size dredger	50,000
Cables removal PSV including containers, curring equipment etc..	40,000
Riggers team 2x6 persons	12,000
ROV including 6 operators	12,000
WTG removal jack up vessel	100,000
Foundations removal jack up vessel	100,000
CTV	7,000

4.4.2 Project organisation rates

The project organisation costs are described in Table 11. The roles which are not available at Ørsted and will be out sourced are the offshore decommissioning manager, the lifting supervisors and the client reps. The external roles are expected to have a 30% mark-up compared to the internal ones. All other roles can be found internally in Ørsted organisation.

Table 11 Project Organisation salaries

Function	Duration (months)	Monthly Rate	Total
Project manager	40	17,500	700,000
Project engineer x3	84	13,500	1,134,000
Cost controller	6	13,000	78,000
Contract manager	6	16,000	96,000
Document controller	18	10,500	189,000
Risk manager	6	12,500	75,000
Quality control manager	12	15,500	186,000
Health and safety coordinator	24	12,000	288,000
Facility manager/warehouse coordinator	12	12,000	144,000
Offshore Decommissioning Manager x2	24	15,500	372,000
Lifting supervisors x4	24	15,500	372,000
Client Reps x4	24	15,500	372,000
Authorised technicians x8	96	11,000	1,056,000
		Total rates	5,062,000

4.4.3 Earnings from scrap

An overview of the earnings from of the wind farm components is presented in Table 12. The prices used are reflecting in the Dutch market (Krommenhoek, 2022). 66% of the monopile is estimated to be removed as the rest is below the seabed.

Table 12 Earnings from scrap

Component	Quantity (units)	Average weight (kg per unit)	Total weight (kg)	Scrap rate per kg (€)	Total profit (€)
WTG tower	94	430000	40420000	0.29	11,721,800
Monopile	94	560340	52671960	0.29	15,274,868
Transition piece	94	375000	35250000	0.29	10,222,500
Array cables	170 (km)	15840	2692800	7	18,849,600
Total earnings from scrap (€)					56,068,768

4.4.4 Overall calculation

The overall ABEX calculation is shown in Table 13. The cost and duration calculations of the previous chapters has been used. A 10% contingency factor is taken into account and a 10% escalation factor. The latter reflects the inflation indexes. The CAR insurance is calculated as approximately the 2% of the total ABEX calculation.

Table 13 ABEX calculation

Scour decommissioning	2,684,814
Cables removal	15,365,476
WTG removal	26,486,839
Foundations removal	32,458,809
CTV	3,285,000
Geophysical survey	1,000,000
Project organisation	5,062,000
Yard rental at Sif	3,000,000
Procurement	500,000
CAR insurance	6,000,000
Sum	€ 95,818,663
Sum including contingency	€ 105,400,529
Sum including escalation factor	€ 115,940,581.88
Earnings from scrap	-€56,068,768.40
Total ABEX	**€ 59,871,813.48**

5 Conclusions

The current study has taken a lot of assumptions into account which is usual for the nature of this type of projects. These assumptions shall be evaluated in the future when more wind farms are being decommissioned. As a result, the ABEX budgets will be estimated more accurately. The future projects will also prove or reject technical solutions which will be developed and which will reduce the costs and make the works more efficient. The current study uses only available techniques in the present.

Because of the uncertainty of the regulatory framework of similar activities, it is advised to start with the planning and regulatory phase process as early as possible to avoid any delays caused by third parties dependencies.

Availability of vessels and logistics in general has been conclude to be a severe risk. Logistics will not be needed only for commissioning but also for decommissioning in the future which will require a massive market expansion in the heavy-lift vessels industry.

Only scour protection and part of the monopiles remains in situ as all other components are removed. In any case that more infrastructure may be left in situ, this will have a positive impact to the total costs.

The main expenses of the project is the removal works of the foundations and the WTGs. This is due to the fact that an expensive jack-up vessel is required for these operations. Additionally, a low number of parts can be transported which increases the number of trips. In the future, larger vessels may become available which will reduce the number of trips. However, the rental day rates of these vessels are expected to increase, also because of the increased demand.

The project organisation costs and the contingency costs by certain circumstances could be reduced/excluded having a positive impact to the overall ABEX calculation. When the decommissioning industry progresses, the uncertainties will be minimised reducing the risks and eventually the contingency costs. Additionally, a company such as Ørsted, with numerous wind farms in operations, could allocate personnel in different decommissioning projects reducing significantly the personnel costs.

The earnings from scrap are quite high affecting positively the overall budget. This is caused by the increase of the metal price during the last 3-4 months. There are no predictions that these prices will be reduced in the near future.

The final ABEX estimation is 20% lower compared to the initial estimation performed during the permit application of the project. This may be the main contribution of this study which could reduce significantly the bank guarantees paid on a yearly basis.

Finally, one of the conclusions of this study, is that because of the uncertainties and the immature nature of decommissioning works, the main contribution is owed to the interviews performed and the personal experience of the author rather than the literature review.

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