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MASTER'S THESIS

Cutting tools/-methods for potential use during decommissioning and dismantling of offshore wind parks

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Cutting tools/-methods for potential use during decommissioning and dismantling of offshore wind parks

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Master Thesis in Master of Maritime Operations

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Cutting tools/-methods for potential use during decommissioning and dismantling of offshore wind parks

Master thesis in Maritime Operations

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Preface

This thesis is the final work for my master's degree in Maritime operation and is credited 30 ETC points. The programme is a joint master between Western Norway University of applied sciences and Hochschule Emden/Leer in Germany.

The idea for this thesis came from my supervisor and leader of the Decom Tool project at the Western Norway University of applied sciences Jens Christian Lindaas.

The Decom Tool project is a part of the INTERREG NORTH SEA REGION Programme, which is an EU-founded programme. The scope for the work in the project is to find experience in the oil&gas industry that can be used in decommissioning of offshore wind turbines. This makes it extra interesting to work with the thesis, my work as a student can help the offshore wind industry to reduce the total environmental footprint.

Reducing the environmental footprint is important, not only in the production, installation, and operation but also in the decommissioning process. By minimizing the environmental footprint in the decommissioning process, the energy delivered from the offshore wind farms become more sustainable. This is an important issue when the world eager for more sustainable energy and needs it to reduce global warming.

This thesis is written as a part of the Decom Tool project, and the specific task is to find cutting tools/-methods used in the oil&gas industry, that can help the offshore wind industry to reduce the environmental footprint from decommissioning of offshore wind turbines.

We have been two students working in the Decom Tool project this semester. I have working with cutting tools/-methods, and Martin Urnes has working with a more general or big picture on decommissioning of wind turbines and see if there are useful experiences from oil&gas.

This has opened for many good discussions about the subject and we don't have to work totally alone, it is always fun to have some to "play" with.

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There are many people I have to thank for the great help provided during the work with this master thesis.

First of all, I will thank my supervisor and leader of the Decom Tool project Jens Christian Lindaas for his support and his constructive feedback. He has also good knowledge of the subsea industry and has many contacts in the subsea companies we have visited, this has been a great advantage in the work.

The Decom Tool project has arranged a project meeting with DeepOcean, Reach subsea, Kværner and AF Decom. They have all welcomed us with great enthusiasm and were eager to share their knowledge and experience.

I will thank my fellow students for two exciting years, it has been two years with hard work and much fun. Martin Urnes deserve a special thank for his cooperation during the last semester. He is working with a similar subject in his thesis, this has opened for many good discussions and brainstorming about offshore wind farm decommissioning.

Summary

The first offshore wind turbine park was built in the nineties and the first was decommissioned in 2001. Since the nineties, the building of offshore wind turbine park has developed to a mature industry, decommissioning is however not mature and there is room for development. The oil & gas industry has long experience with decommissioning and one of the goals for the project is to use experience from the oil & gas industry to develop tools/-methods for decommissioning of offshore wind turbines.

This paper is a part of the Decom Tools project, this is a project funded by Interreg North Sea Region, a European regional Development Found. The aim of the project is to reduce the decommissioning cost by 20% and the environmental footprint by 25% (measured in CO2 equivalents). The base case for measuring cost and environmental footprint is a reverse installation of offshore wind turbines. The task for the work with this paper is to use experience with cutting tools/-methods from oil & gas and use them to develop cutting tools/-methods for decommissioning of offshore wind turbines. Sheringham Shoal offshore wind park and the decommissioning paper provided by Equinor was used as a base case for this paper, tools/-methods used in the decommissioning paper was compared with the experience from the companies and new tools/-methods proposed by the writer. Sheringham Shoal offshore wind park is located in the UK, and the solutions presented are based on UK law and regulation.

Four companies working in the oil & gas industry was consulted to gather experience. Two of the companies was contractors and two was working with decommissioning of offshore oil & gas structures. Members of the Decom tools project visited the companies for a workshop. A questionnaire provided by the Decom Tools project was sent to the companies in advance for our visit and workshop with the companies.

The experience from the companies was compared and used to develop a new tool/-method for decommissioning of offshore wind turbine foundation. The method is based on the companies preference for diamond wire saw and their aversion against dredging. The new method is to cut the monopile on the seafloor with a diamond wire saw and drive the monopile further down in the seabed with a hydraulic hammer.

Abstract

Offshore wind turbines have been installed in a large number in the North Sea and are a mature industry, decommissioning however has only been done with a few offshore wind turbines and are based on reversed installation.

This paper use experience from the oil & gas industry to develop a new tool/-method for decommissioning of offshore wind turbine foundation. Companies in the oil & gas industry have shared their experience with the writer trough questionnaire and workshops.

The proposed method is based on the companies preference for diamond wire cutting and their aversion against dredging. The proposed method uses a diamond wire saw to cut the foundation at the seabed and hydraulic hammer to drive the remaining foundation down in seabed.

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Abbreviations

Abbreviation	Description
AWJ cutter	Abrasive Water Jet cutter
DP	Dynamic Positioning
ECM	External Cutting Manipulator
HAZID	HAZard IDentification
HSE	Health, Safety and Environment
HSE	Health Safety and environment
HVL	Heavy Lift Vessel
HVL	Høgskulen På Vestlandet, Western Norway University of Applied Science
ICM	Internal Cutting Manipulator
IMO	Internationale Maritime Organization
IMR	Inspection Maintenance and Repair
MP	Monopile
MW	Mega Watt
P&A	Plug and Abandon
PTV	Personnel Transfer Vessel
ROV	Remotely Operated Vehicle
SoW	Scope of Work
TP	Transition Piece
UNCLOS	United Nations Convention on the Law of the Sea
WTG	Wind Turbine Generator

1. Introduction

1.1 Research Question

The research question is part of the Decom Tools project founded by Interreg North Sea Region, a European regional Development Found. The aim of the project is to reduce the decommissioning cost by 20% and the environmental footprint by 25% (measured in CO2 equivalents). The base case for measuring cost and environmental footprint is a reverse installation of an offshore wind turbine.

The aim for the master thesis is to use experience with cutting tools/-methods from offshore oil and gas industry, see if the tools/-methods are suitable for use during decommissioning of offshore wind farms and suggest new/-modified cutting tools/-methods.

The research question for this thesis is:

Cutting tools/-methods for potential use during decommissioning and dismantling of offshore wind parks.

1.2 Providing the answer

To answer the research question, information is gathered from four sources:

- Literature study
- Internet investigation.
- External expertise/experience (Visit companies)
- Experience in the Decom Tools project team at HVL (Høgskulen på Vestlandet)

1.3 Background

First offshore wind park in the world was Vindeby, Denmark, built in 1991, in 2017 it was one of the world's first offshore wind park to be decommissioned. The wind park consists of eleven 54 metres high turbines, each with a capacity of 0,54 MW. The water dept in the area is 2 to 5 meters and the turbines were mounted on a concrete gravel foundation. The offshore park was completely decommissioned, and the site was left as close as practically possible to the state it was before installing the wind park.

After the construction of Vindeby offshore wind park, the offshore wind parks have grown in size, both in numbers of wind turbines, the size of wind turbines and water depth on the site.

Fig.1 shows the cumulative installed capacity in MW (MegaWatt) and annual installed capacity in MW for offshore wind turbines installations in Europe.

Fig. 2 shows the installed capacity, the number of wind farms and the number of wind turbines for each country at the end of 2017.

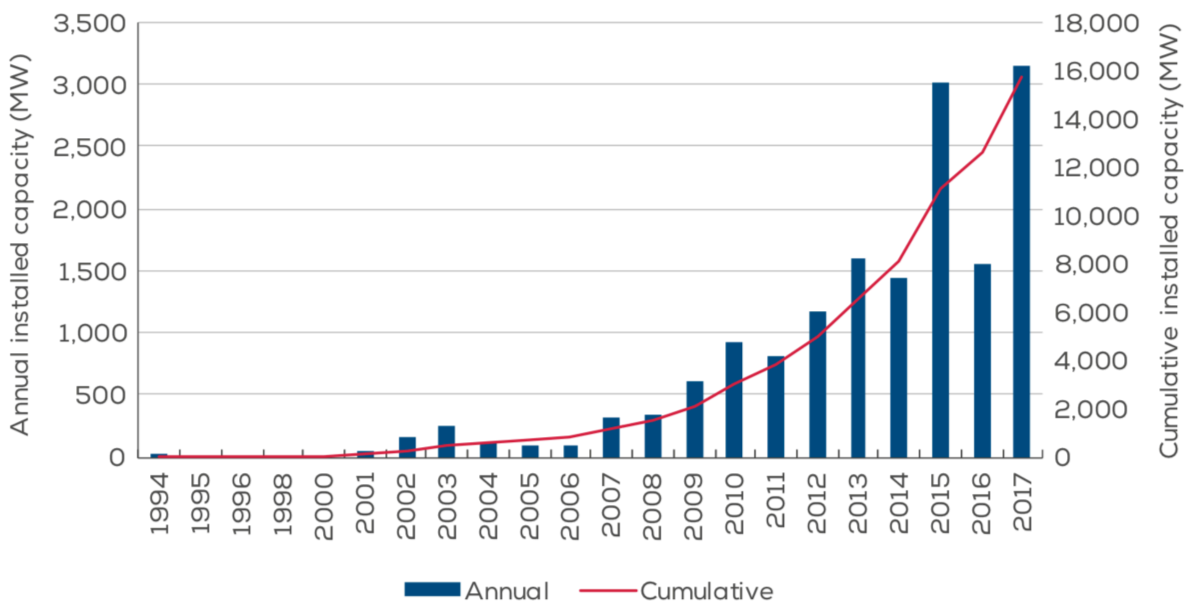

Figure 1 Cumulative and annual offshore wind turbine installation in Europe in MW [1]

COUNTRY	NO. OF FARMS	NO. OF TURBINES CONNECTED	CAPACITY INSTALLED (MW)	CAPACITY INSTALLED/ DECOMMISSIONED IN 2017 (MW)
UK	31	1,753	6,835	1,679
GERMANY	23	1,169	5,355	1,247
DENMARK	12	506	1,266	-5
NETHERLANDS	7	365	1,118	0
BELGIUM	6	232	877	165
SWEDEN	5	86	202	0
FINLAND	3	28	92	60
IRELAND	2	7	25	0
SPAIN	1	1	5	0
NORWAY	1	1	2	0
FRANCE	1	1	2	2
Total	**92**	**4,149**	**15,780**	**3,148**

Figure 2 Number of wind farms with grid-connected turbines, number of turbines connected and number of MW grid-connected at the end of 2017 per country. [1]

Design life for a wind turbine is 20 years, after this time the wind turbine enters the lifetime extension phase. Before the turbine can be operated in the lifetime extension phase, the wind turbine must be assessed regards to its potential for lifetime extension. This evaluation consists of an analytic part, a practical part, and a financial part. Fig 3. shows the different phases in the total lifetime for a wind turbine.

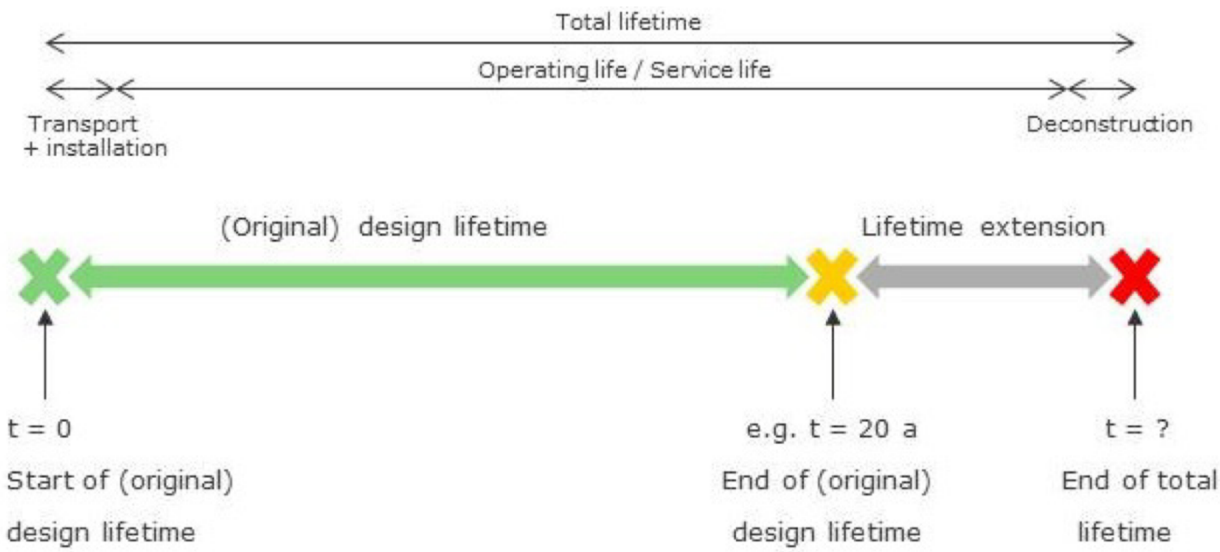

Figure 3 Lifetime of a wind turbine. [2]

When the wind turbine reaches the end of the lifetime, the wind turbine must be decommissioned or repowered. Repowering normally involves some degree of decommissioning. Repowering the offshore wind park involves all activity from the change/upgrading of the generator to total decommissioning and reuse of the site.

The offshore wind park industry is a relatively new industry that has developed from and after Vindeby, up to recently the focus has been on developing and building offshore wind park, but as an increasing number of wind turbines reach their end of a lifetime the industry has to focus on developing effective decommissioning and repowering methods.

Fig 4. shows projected annual offshore wind decommissioning based on WindEurope statistics from 2016 for the annual capacity of offshore wind installed in Europe. [3]

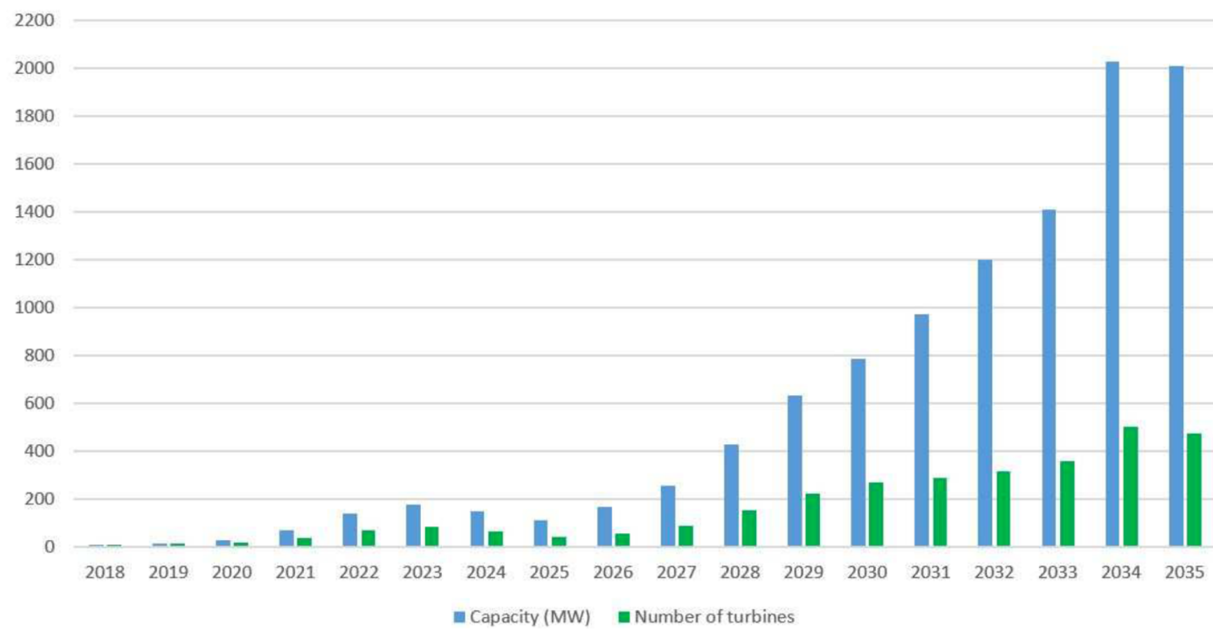

Figure 4. Estimated annual offshore wind decommissioning in Europe. [3]

1.3.1 International and UK regulation regarding decommissioning of offshore structures.

The Sheringham Shoal offshore wind park in the UK is chosen as a base case for the master thesis, it is located in the Greater Wash, about 20 kilometres off the Norfolk coast, in the south-west part of the North Sea.

UNCLOS Article 60 sets out requirements in respect of abandoned or disused installations or structures in the countries exclusive economic zone.

"Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent international organization. Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States. Appropriate publicity shall be given to the depth, position, and dimensions of any installations or structures not entirely removed." [4]

The competent international organization to deal with this subject is IMO and after considering the draft from the Maritime Safety Committee and Marine Environment Protection Committee IMO adopted the resolution.

Resolution A.672(16) adopted on 19 October 1989.

Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone

This guideline establishes criteria for the removal of offshore installation and structures and the main criteria are that unused installation shall be removed, but there is some exception from this. The coastal State with jurisdiction over the installation shall perform a case-by-case evaluation if partially removing is allowed, taking into account the following matters:

- *Any potential effect on the safety of surface or subsurface navigation, or of other uses of the sea;*
- *the rate of deterioration of the material and its present and possible future effect on the marine environment;*
- *The potential effect on the marine environment, including living resources;*
- *The risk that the material will shift from its position at some future time;*
- *The costs, technical feasibility, and risks of injury to personnel associated with removal of the installation or structure; and*
- *The determination of a new use or other reasonable justification for allowing the installation or structure or parts thereof to remain on the sea-bed.* [4]

IMO also:

RECOMMENDS that Member Governments take into account the aforesaid Guidelines and Standards when making decisions regarding the removal of abandoned or disused installations or structures. [4]

The Government of UK which is a Member Government has developed Guidance notes for the industry to assist businesses in understanding their obligation regarding decommissioning of offshore renewable energy installations under the Energy Act 2004.

Taking into account the international obligation the guidance sets out some examples of a solution other than full removal.

- *Structures which will be reused for renewable energy generation*
- *Structures which serve a purpose beyond renewable energy generation*
- *Foundations and structures below the sea-bed level*
- *Cables buried at a safe depth below the sea-bed*
- *Scour protection materials* [5]

Decommissioning in UK waters can after a case-by-case evaluation, instead of removing everything, be performed as follow:

- Remove all installations down to 2 meters below the seabed.
- Leave cables buried in situ
- Leave scour protection in situ.

This guidance applies for UK waters only, offshore wind park owners must comply with guidance and regulation for the coastal State with jurisdiction over the installation.

2 Theory

The Sheringham Shoal Offshore Wind Farm is chosen as a base case and construction, installation and planned decommissioning phase will be described. Figure 5 shows layout of Sheringham Shoal wind park with offshore wind turbines and export cables.

Sheringham Shoal offshore wind turbine consists of;

- Monopile driven into the seabed for support and to make a base for the wind turbine. Figure 6 shows the monopile and transition piece.
- Transition piece: mounted and grouted to the monopile to make a foundation for the tower.
- Tower: mounted on the transition piece to achieve sufficient height for the nacelle.
- Nacelle: is mounted on top of the tower and is the heart of the wind turbine. The nacelle contains a generator, gear, hub, and control system for the wind turbine.
- Blades mounted on the hub. Figure 7 shows mounting of turbine blades.
- Inter-field cables between the wind turbines and the substation.
- Export cables to the shore stations.

Cutting needed for decommissioning as it is planned will be described at the end of the chapter. As monopile is the preferred support structure in the industry and the base case use monopile, the other alternatives for support structure will be presented as a figure in Appendix J.

2.1 Base Case

Sheringham Shoal offshore wind park in the UK is located in the Greater Wash, about 20 kilometres off the Norfolk coast, in the south-west part of the North Sea.

The UK has by 2017, 6835 MW wind power installed with 1753 offshore wind turbines installed. This is 43% of all offshore wind turbines installed in Europe [1]. The Sheringham Shoal is partly owned by a traditional oil company (Equinor, former Statoil), Equinor has also written the decommissioning document, this is a link from the offshore oil industry to the offshore wind industry. This makes Sheringham Shoal well-suited as a base case.

Facts and figures about the Sheringham Shoal Offshore Wind Farm [6]:

- 317MW of capacity
- Covers an area of approximately 35 km2
- Water depth 17 to 22 meters
- 88 Siemens wind turbines, each with a capacity of 3.6MW.
- Nacelle, 140 tonnes
- Turbine blade length 52 meters, weight 20 tonnes
- Turbine tower height 80 meters, mounted in two parts, with a total weight of 300 tonnes
- Monopile 4,7-5,2 meter in diameter, 44-61 meter of length, 0,060-meter wall thickness and a total weight of 375-530 tonnes.
- Grout between monopile and transition piece is a concrete-grout and weight from 20 to 100 tonnes.
- Transition piece 22 meters height and a weight of 200 tonnes
- Two 900 tonne offshore substations standing on monopile.

2.1.1 Installation

The installation of the wind turbine park was commenced in 2009 and the park was fully installed and operational by late summer 2012. Installation of monopile and transition piece was conducted with crane vessels. The work was started with the heavy lift vessel “Svanen”, she is a twin hull vessel of 103 meters and a lifting capacity of 8700 tonnes. The experience with “Svanen” shows that she was too vulnerable for wind and sea state and the contract was terminated in autumn 2010. In April 2011, “Oleg Strashnov” a 183-meter vessel that can lift 5000mt continued the installation. Installation of tower, nacelle and turbine blades was conducted with a jack-up vessel, the vessel is standing on the seabed during crane operations to form a steady platform for crane operations.

The monopile is the first part installed, it is driven approximately 30 meters into the seabed with a hydraulic hammer and reaches a few meters above sea-level. Geotechnical conditions for the soil were identified based on surveys, borehole campaign, and laboratory tests. Based on this data, each foundation was designed and fabricated specifically for its specific location. Appendix B. shows the result of the surveys for each wind turbine location.

The transition piece is mounted on the monopile and is the connection between the monopile and tower, it is grouted to the monopile and is equipped with a boat landing arrangement and work platform.

The tower is manufactured in two parts and is transported to the site standing vertical on deck on the jack-up vessel, hoisted in place and bolted together inside the tower. The nacelle is bolted in place on top of the tower. Finally, the blades are bolted on the hub.

The inter-field cables are buried between the wind turbines and installed through a J-tube to protect the cable. The J-tube is mounted through the monopile at the seabed and goes up to the top of the transition piece.

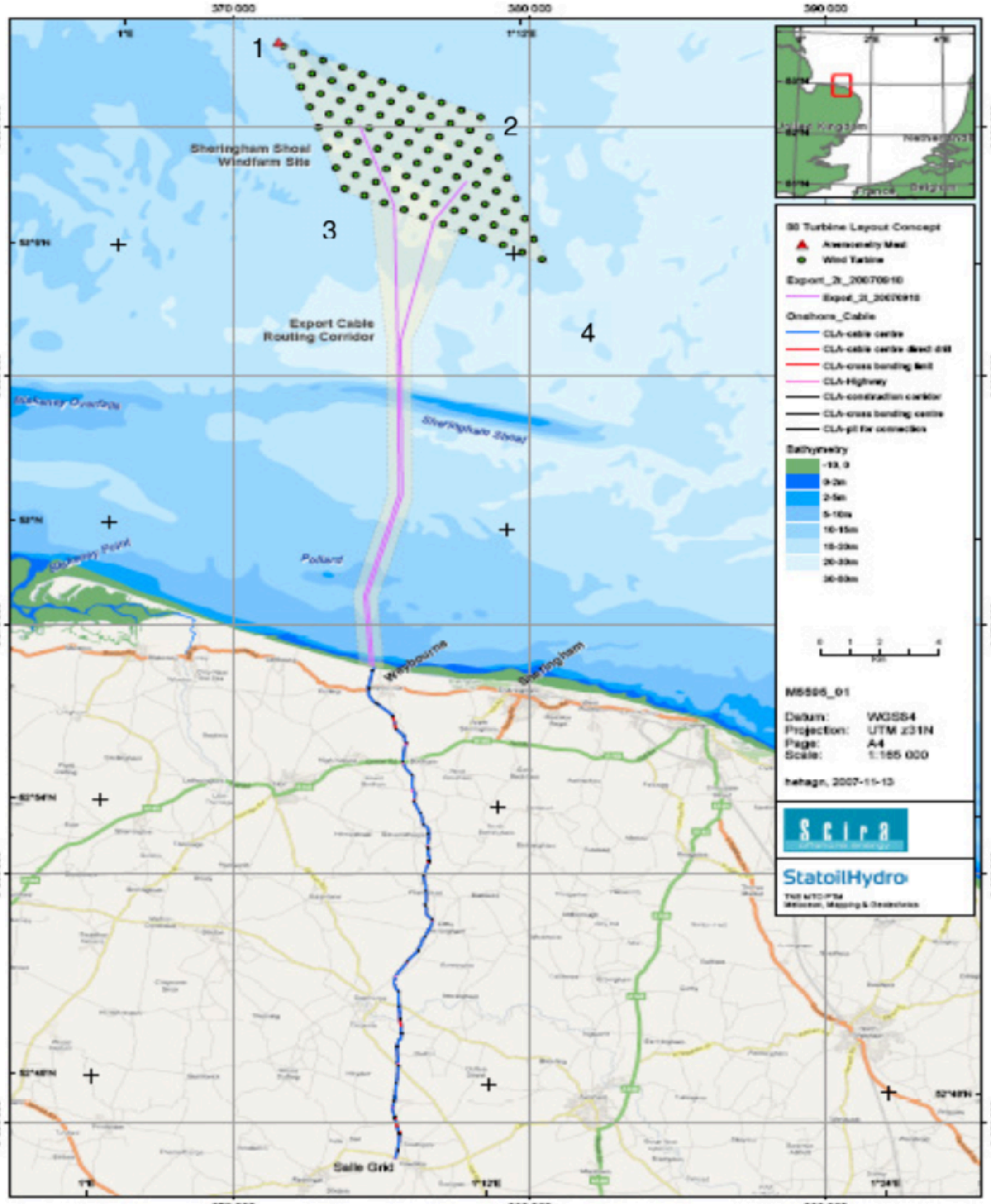

Figure 5 Sheringham Shoal layout [6]

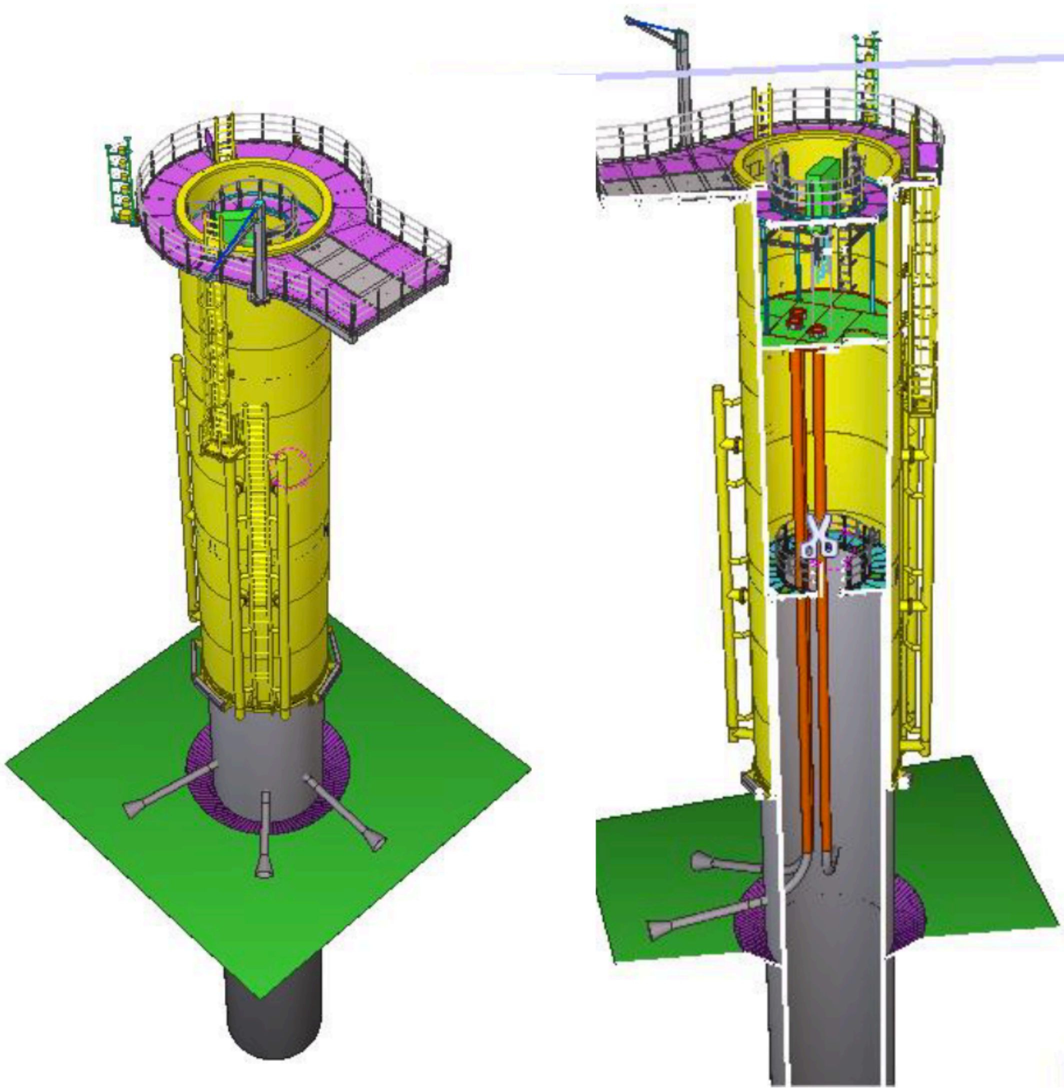

Figure 6 Monopile with transition piece, Sheringham Shoal type. [7]

Figure 7 Mounting of blades at Sheringham Shoal using jack up vessel. [6]

2.1.2 Decommissioning

The decommissioning process is planned and described by Equinor in the document; Decommissioning Programme Rev.6.0. [6] This document describes the planned decommissioning prosses and related costs.

The decommissioning is planned in three campaign;

- 1st Campaign – Preparation of WTG (Wind Turbine Generator) + Foundation
- 2nd Campaign – WTG + Foundation Removal
- 3rd Campaign – Rock-dumping and completion

The 1st Campaign is a preparation campaign and will be performed to clarify the wind turbine for the lifting operation, the tasks for the campaign are listed in Table 1. Personnel will be transported to the site using PTV`s (Personnel Transfer Vessel)

Task #	Task
1	Clearing of loose items in nacelle and tower.
2	Installation of temporary lighting in tower and nacelle
3	Cutting of wiring at separation points between nacelle and tower, tower sections and at cutting points in TP (Transition piece)
4	Preparation of bolts on rotor blades and tower flanges. Cleaning and application of penetrating oil to help the disassembly.
5	Preparation of a temporary power supply for the high-speed motor to turn the rotor. Cabling from the nacelle to the base of the tower, the motor will be powered from the jack-up for the removal operation.
6	Installation of a ventilation system below airtight platform. The void space below the airtight platform is designed to be oxygen free to prevent corrosion inside the MP (Monopile). Because work will be performed below this platform during the removal this space must be ventilated before the removal.
7	Removal of the elevator from the tower. The elevator in the tower will be parked at the base of the tower and the steel wires, power cables, and additional systems are dismantled and stored at the base of the tower

Table 1 Work tasks to be performed during the 1st campaign [6]

The 2nd Campaign is the most comprehensive and cost incentive campaign with the use of two jack-up vessels with similar capacity as Pacific Orca of Swire Blue Ocean. The Pacific Orca is 160 meters long self-propelled and can lift 1200 tonnes. She has deck capacity to carry 5 complete wind turbines with the foundation on deck and transport them to shore base.

The decommissioning of WTG structures, which include blade, hub, nacelle, and tower is planned as a reversed installation.

The foundation is planned with two cuts, one at the transition piece just above the grouted connection and one at monopile two meters below the seabed. The J-tubes are planned with two cuts, one at transition piece and one where they exit the monopile. The subsea cutting of J-tubes is planned with the use of divers and diamond wire saw.

The prosses is described in the document as follow:

Removal of the WTG is done using a reversed installation method where tools such as angle grinders and plasma cutters are used to remove bolts that are not possible to remove using normal methods. Plasma cutters are used in place of acetylene torches to remove the need for combustible gasses with their accompanying HSE risk.(Health, Safety and environment)

While the tower is removed the foundation is prepared for removal. A cutting tool is fitted below the airtight platform in the TP, just above the lower platform at z=7400 mm. While this is installed the J-tubes are cut where they exit the MP and at z=7400 mm. The vibration dampers installed on the J-Tubes are cut to release the J-Tubes.

After removal of the WTG, rigging is prepared to lift the top of the TP. Cutting is started while the crane supports the load above the cut. With the top piece of the TP removed the internal J-tubes can be lifted out of the MP. (monopile)

After the j-tubes have been removed internal access to the lower end of the MP is possible. An ICM (Internal Cutting Manipulator) is used to release the external j-tubes and cut the MP at 2 meters below the mud-line [6].

The 3rd campaign consists of rock dumping in the hole after the monopile and third-party inspection to provide documentation.

2.1.3 Cutting requirement base case

Cutting requirements 1st Campaign	Cutting solution
Bolts	Grinder
	Plasma cutter
Cable and wire	Not specified

Table 2 Cutting requirements 1st Campaign

Cutting requirement 2nd Campaign	Cutting solution
Bolts	Grinder
	Plasma cutter
Tower upper cut	Plasma cutter mounted on rails for automated cutting
Boat landing	Not specified
Tower lower cut	Abrasive water jet mounted on ICM (Internal Cutting Manipulator) for automated cutting
J-tubes	Diamond Wire saw

Table 3 Cutting requirements 2nd Campaign

2.2 Decommissioned Offshore wind farm

2.2.1 Vindeby Offshore Wind Farm

Vindeby offshore wind park, Denmark, was installed in 1991 and decommissioned in 2017. The turbines were 0,45MW 54 meters and the total number was 11. The site should not be used for wind park after decommissioning and should be left as close to the original state as possible.

The decommissioning was performed as a reversed installation, blades, nacelle, and tower was dismantled and taken down using a crane on a jack-up vessel. The pieces were then taken to shore for further demolition and recycling. The concrete gravity foundation was broken down on site using hydraulic demolition shears, collected and taken to shore. Cables were taken up and recycled.

2.2.2 Lely Offshore Wind Park

Lely wind farm was located in Ijsselmeer, Netherlands, consist of four wind turbines with a total capacity of 2MW. The wind farm was built in 1992 and decommissioned in 2016. The decommissioning was performed as a reverse installation, the nacelle with blades was lifted down. The 40 meters tower was lifted down in two pieces and the monopile foundation was retracted using a vibratory hammer. The operation was performed from jack-up barges and crane vessels.

2.2.3 Yttre Stengrund Offshore Wind Park

Ytre Stengrund offshore wind farm was located in Kalmar Sound, Sweden consists of five 2MW 60 meters, built in 2001 and decommissioned in 2016. The decommissioning was performed as a reverse installation. The hub with blades, nacelle, and tower was taken down by the use of a crane. The concrete foundation was cut off level with the seabed. The cables removed and the site left as close to original as possible.

3 Methods

The information is gathered from websites to the company delivering equipment to the oil and gas industry, google search for complementary information, experience in the Decom Tools team and experience gathered from companies working in the industry. YouTube has also been a source to understand how the wind turbine is built and mounted. When using YouTube, it is important to consider the source, I have used movies with an interview with a representative from Equinor.

The articles databases Web of Science and Scopus is used to search for scientific articles/information about cutting tools/-methods and complementary information about wind turbines.

The search string "cutting method, steel" resulted in 3395 articles, this was reduced to 63 when "underwater" was added to the search string. If "underwater" was replaced with "subsea" the result was 4 articles, with "decommissioning" the result was 4 articles. The titles from the search result were analyzed, in relevant articles the abstract was studied for relevance. There was no relevance in the resulting articles.

The search string "wind turbine" resulted in 21.235 articles, this was reduced to 3.033 when "offshore" was added to the search string. When "decommissioning" was added to the search string the result was 20 articles. These 20 articles were considered trough title and abstract, there was no relevance in the articles.

In Scopus the search string "wind turbine offshore decommissioning" resulted in 250 documents, "cutting method steel decommissioning" resulted in 98 documents and "cutting method steel subsea" resulted in 77 documents. The documents titles here analysed and some of the abstract were studied for relevance. There was no relevant information regarding cutting tools/-methods used in the oil & gas industry. There was some information regarding the novel cutting method and development of the existing cutting method for use in the decommissioning of atomic plant. The tools/-methods discussed in the papers was special designed for decommissioning of atomic plants and there was no relevance for decommissioning of offshore wind turbines.

There was no relevant information to find in Web of Science and Scopus, as a result of this, the main source for information regarding experience with cutting tools/-methods used in the oil & gas industry is gathered directly from companies in the industry.

The companies that were asked to participate in the project are local companies with long and worldwide experience as contractors in the oil & gas industry. There were two companies with experience from IMR, ROV, Survey, Construction Support and Decommissioning Services to the

oil & gas industry. Two of the companies are working with decommissioning of offshore structures and have their own site onshore for the demolition of the structures.
The Decom Tools project arranged a workshop in Haugesund 26.04.2019 with participants from companies from oil & gas, public administration, students and others with interest in the field of decommissioning of offshore wind turbines.
The questionnaire used in the excursion is provided by the Decom Tools project and is used in all parts of the project. The questionnaire was sent to the participant in advance and was discussed in the workshop arranged on each excursion. The excursion was organized as a workshop to ensure an open discussion to transfer experience to the Decom Tolls project.

3.1 Cutting tools/-methods used in the oil & gas industry

This chapter describes different cutting tools/-methods used in the oil & gas industry, both over and under water.
There are two main principles for splitting material, removing material and cut material. Removing material can be done by heat or by mechanical methods, typical tools are saw, grinding and oxy-fuel. Cutting materials are done by guillotine, scissor or explosives. Regardless of cutting methods, it is important to consider all safety aspects for the chosen method, the safety must be considered for people, environment and property. The cutting operation is part of the decommissioning operation and cutting operation must be a part of the HAZID (HAZard IDentification) analysis.
Cutting quality depends on equipment and cutting speed, the quality on the cut is not considered in this paper: When used in decommissioning the main target is to cut the materials as efficiently as possible.
Cutting can be done with an automated system or hand-held system. With an automated system, rails or chain is mounted on the item being cut and the cutting device follow this at a constant speed. An automated system can also be built as an integrated part of the cutting tool/system. Some of the benefits of an automated system are safety for the operators, optimized cutting speed and availability to the cutting area.

3.1.1 Saw

The saw is a simple well-known construction with a wide range of available blades for use on different materials. There are different saw principles available, a circular saw is the most common but oscillating saw is also used.

The circular saw is using a circular blade with teeth or friction elements to remove material, shape, and material on teeth or friction elements determine the characteristic of the saw.
The oscillating saw is using a straight blade which is moved back and forth in an oscillating movement. The blade has one cut direction and is lifted from the material when moved in the other direction.

Different saw blade:

- Teeth made of the same metal as the blade and hardened a simple and cheap blade.
- Diamant segment, industry diamante molded in segment mounted on a metal blade. More diamante is exposed during use as the molded material is worn down.
- Hard metal segment mounted on a metal blade. A durable blade when used according to manufacturer specification.

Cutting speed depends on material cut in, saw characteristics, blade speed, and chip removal. Depending on the blade and material cut in, there can be a need for cooling of the blade, this is not a problem when used underwater.
The success criteria for a cut with saw involve choosing saw type and blade, consider feed rate and need for cooling of the blade. Power for the saw can normally be delivered from the ROV, this makes the saw easy to mobilize and it doesn't require own technicians to operate it.

Figure 8 ROV Rotary Saw [8].

Figure 9 Guillotine oscillating saw [9].

3.1.2 Chain saw

The chain saw has a sword with a running cutting chain. The teeth on the chain cut the material, shape, and material on the teeth determine the characteristic of the saw. We normally use a chain saw to cut trees, but if we use a chain with carbide or diamond segment teeth, the saw can cut other things like concrete and cast iron.

The motor on the saw can be hydraulic, petrol, pneumatic or electric and can be used subsea as well as over water. When used over water the diamond segment chain must have water both for cooling and cleaning of chain and sword. The chain saw is relatively slow when used on concrete, but it is easy to mobilize, it is typically used on small jobs and to correct errors.

Figure 10 Chain saw [10].

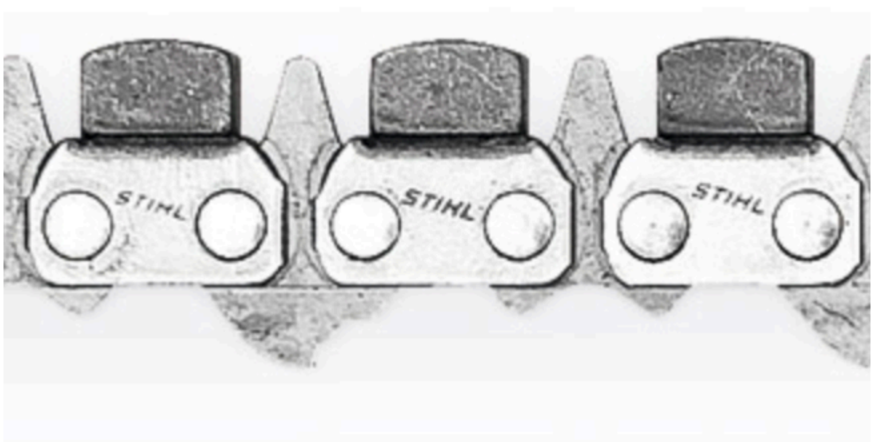

Figure 11 Chain with diamond segments [10].

3.1.3 Wire

Wire cutting tools use wire with industry diamond segments to remove a part of the material being cut. The diamond saw can cut through all material softer than diamond. The diamond wire can be arranged on a saw for small structures, Figure 12 Shows two different types, one hold by the ROV manipulator and one that holds around the object being cut and the wire saw is fed down as it cut through. For big structures, the wire can be arranged around the structure and back to the operating module, this is used for cutting of shipwreck.

In a subsea configuration, the saw is normally powered by the ROV and it doesn't need own technicians to run the saw. Cutting speed is relatively slow but the saw is easy to mobilize Wire cutting saw can be used both over and under water, when used over water the wire must be cooled with cooling liquid e.g. water.

Figure 12 Diamond wire saw. [11]

3.1.4 Oxy-fuel

Oxy-fuel is a technique using fuel-gas and pure oxygen to oxidize the metal in an exothermic reaction. The fuel gas can be acetylene, propane, hydrogen, ethane. Acetylene is the most used fuel gas and the flame temperature is 3150° C when used together with pure oxygen.

Fig 13. shows different flame temperatures, preheat time and cutting speed for different fuel-gasses. The cutting torch has one centre nozzle for oxygen surrounded by nozzles for preheating flame. When starting a cut, the metal is preheated to around 960° C, the metal has now lost its protective properties against oxygen but it's still solid. Pure oxygen with high pressure is applied through the centre nozzle, this starts an exothermic reaction where the unprotected metal oxidizes into Metal Oxide and heat. The oxide or slag has a lower melting point than the metal being cut, and the oxygen can blow it away. The heat from the exothermic reaction heat up the metal, this is a continuous reaction and the torch can be moved to create a cut.

For this technique to work the metal must react with oxygen and the slag must have a lower melting point than the metal being cut, this is applying for carbon and carbon manganese steel.
Acetylene gas is unstable at a pressure above 2,0 bar and is stored on special gas cylinders that allow storage up to 20 bar to prevent decomposing to carbon and hydrogen [12]. Acetylene is withdrawn from the cylinder through an acetylene cylinder regulator with a maximum output pressure of 1,5 bar [13].
Due to the restricted output pressure of acetylene, it cannot be used on deeper water than approximately 10 meters, on deeper water hydrogen is the preferred fuel-gas.

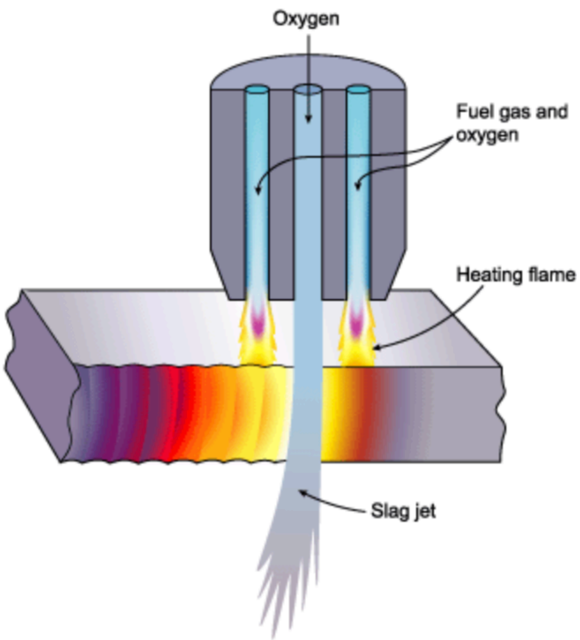

Figure 13 Oxy-fuel cutting nozzle [14].

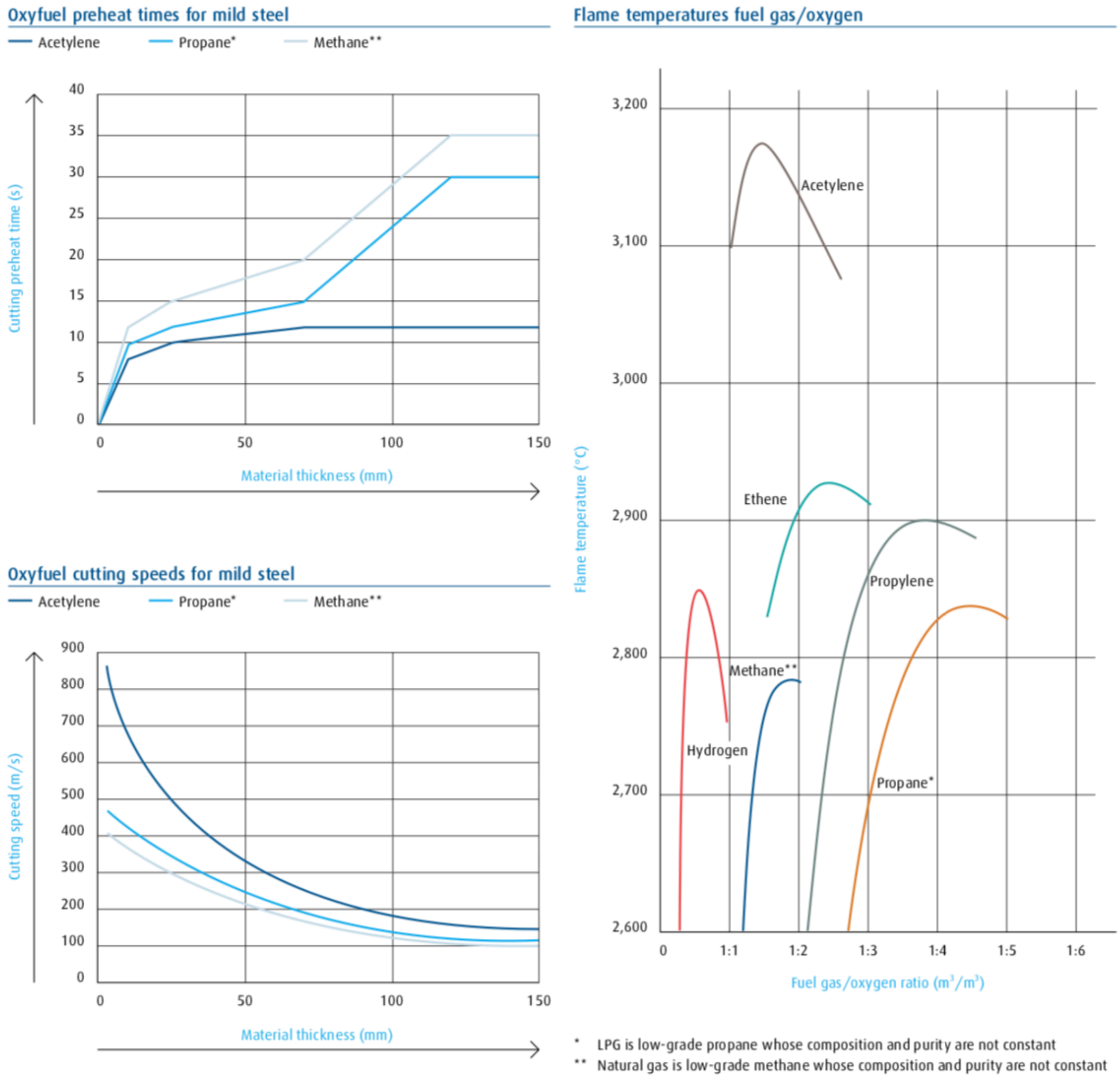

Figure 14 Flame temperatures fuel gas, oxygen/air [15].

3.1.5 Laser

Laser cutting is using a focused laser beam to heat metal, the heated metal is either blown away with air or N_2or oxidized with the use of pure Oxygen. There are two main principles to make a laser beam, CO_2, and Fiber laser.

The CO_2 laser beam is created in a laser resonator and is send over a series of mirrors to enhance it. The laser beam is then concentrated in a focus point by a focus lens in the cutting nozzle. Figure 15 shows the CO_2 laser head and different focus position relative to the workpiece.

Laser cutter

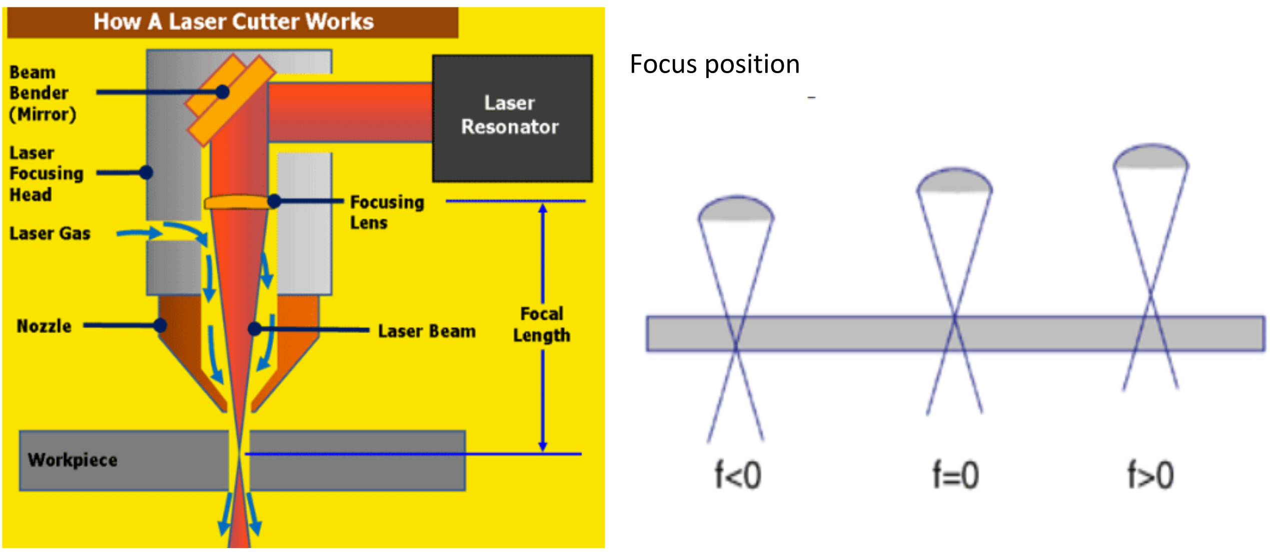

Figure 15 Laser head and Focus position [16].

In a fiber laser, the light is delivered from a pumping diode and generated and enhanced inside an optically active fiber. The laser light is transported from the generator to the nozzle with optical fiber where it goes through a focusing lens and to the workpiece. This is a more robust construction than the CO_2 laser with its mirror that is very vulnerable for shocks.

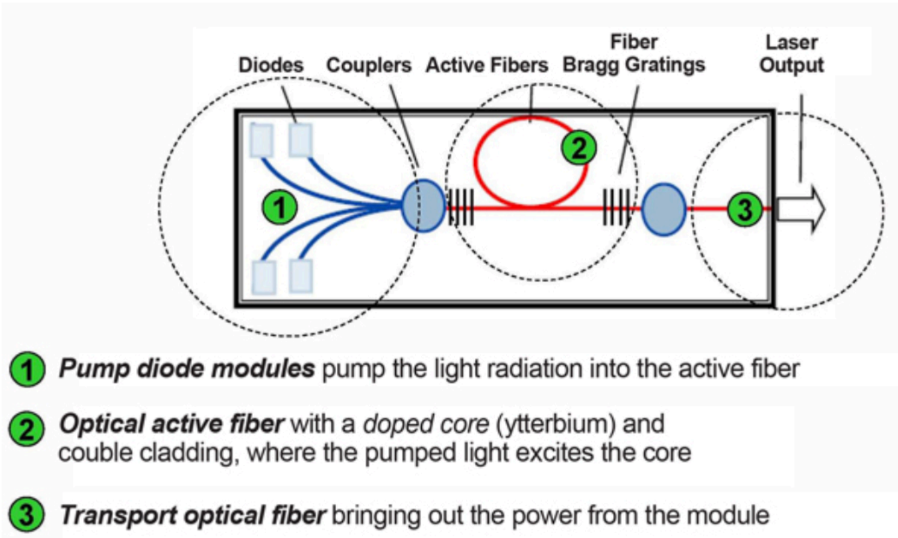

Figure 16 Fibre laser [17]

Laser cutting is normally used for metal plates up to 20mm in CNC machines to cut complex patterns, but it can also be used in handheld configurations. Laser cutting can be done subsea. The Welding Institute cut a 12mm steel plate submerged in water with a speed of 0,4m/min. The gas delivered through the nozzle creates a gaseous environment around the nozzle and workpiece, this helps the laser to maintain the temperature in the steel [14]. For both principles, the distance from the focus lens to the focus point is constant. The focus point is adjusted after plate thickness and material. Cutting in carbon steel up to about 6 mm the focus point is positioned above the surface, for thicknesses above 8 mm the focus point is placed at surface. Cutting in stainless steel or aluminium, the focus point is positioned at about 2/3 the sheet thickness in the sheet. It is therefore important to keep the nozzle distance to the workpiece constant during cutting operations. Figure 15 shows different focus point.

3.1.6 Plasma

Plasma cutting is using heat from gas in the plasma state, the fourth state of matter, and can cut all electrically-conductive materials.

Gas in the plasma state is electrically-conductive and will create an arc between the electrode and workpiece, the gas is constricted through a nozzle, this increased temperature, and velocity of the plasma. The temperature can reach 20.000°C and the velocity can reach the speed of sound.

DC-energy is transferred through the plasma and creates a continuous stream of gas in the plasma state. The heat from the plasma gas is melting the workpiece and the gas constricted through a nozzle will blow away the melted metal.

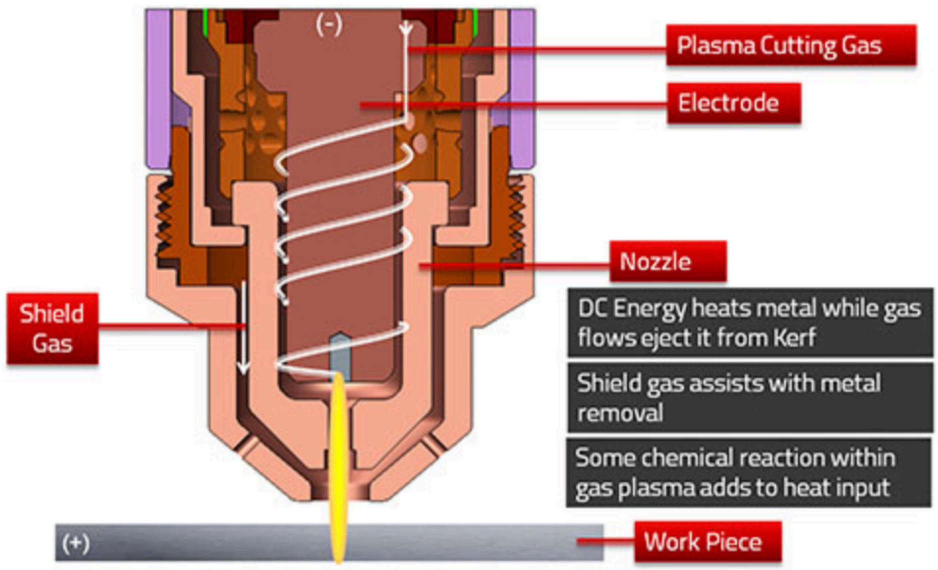

Figure 17 Plasma cutting nozzle [18]

Plasma cutting was developed to cut in materials not meeting the criteria for Oxy-fuel cutting, the oxide or slag must have a lower melting point than the metal being cut so the oxygen can blow it away. The gas used in plasma gas cutting depends on the material to be cut. Oxygen can be used when cutting mild steel, the oxygen will oxidize the steel and increase cutting speed. Air is also used, it consists of approximately 20% oxygen and 80% nitrogen, is free and you don't run out of gas.

Plasma cutting is used in CNC machines and manually system, both over and under water. It has high cutting speed concentrated heat transfer and a small area affected by the heat.

3.1.7 Grinding

Grinding is an operation where friction from a circulating blade scratches away material, both the blade and material are scratched away. The grinder is usually used for small jobs for cutting or smoothing of surfaces. Used subsea, the grinder is powered and controlled by the ROV, on the surface, the grinder is handheld and powered by air or electricity.

The grinder is very easy to mobilize, powering and use. It is important to follow manufactures instruction on the use of grinding disk e.g. rotation speed material to cut, cut or smoothing disk, wet or dry use.

3.1.8 Water jet with abrasives

Water jet with abrasives is like the name indicates, use of high-pressure water with abrasives to cut materials. The water is boosted up to ca. 2500 bar, abrasives is added, and the mixture is delivered through a nozzle and the energy from the water and abrasives cut the material. Water jet with abrasives is a very versatile process and can cut through almost any material. Figure 18 shows three alternatives, pure water, abrasives added by an injector-nozzle and abrasives added as slurry.
The slurry system can be used on water-depth up to 600 meters, cut metal with thickness up to 500mm and concrete with thickness up to 1500mm, cutting speed for 50mm steel is 120mm/min [19]. Water jet cutting requires the mobilization of several containers on deck and own technicians to run it, this makes the system best suited for bigger jobs or campaign with several jobs. The nozzle can be mounted on different manipulators and can cut a pipe from outside or inside. Figure 19 shows a manipulator for inside-out cutting, it is self-centered and can rotate the cutting nozzle. TWI have built manipulators to cut pipes up to 95” in diameter from inside as standard equipment. [14].

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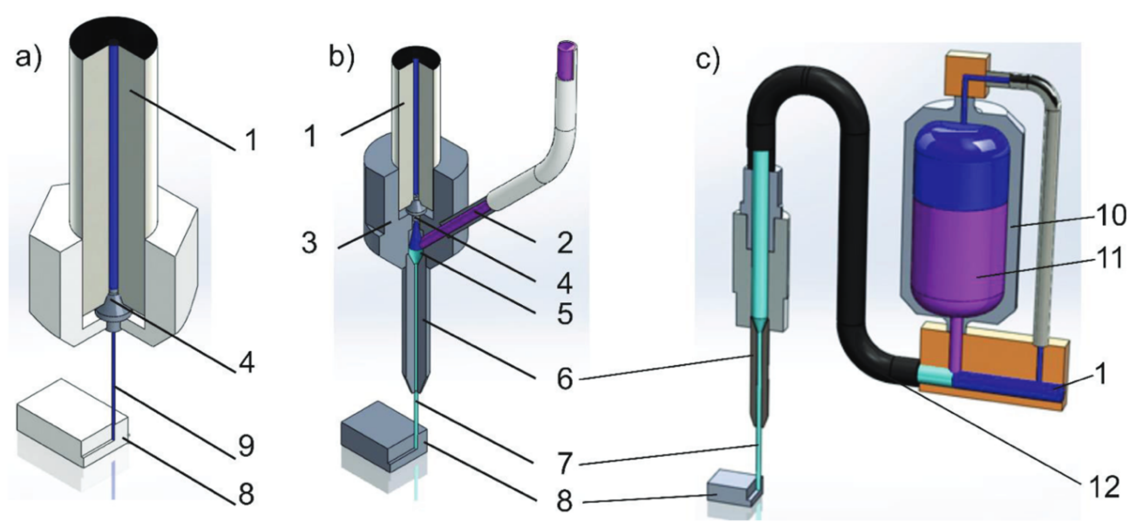

Figure 1. Schematic diagram of: a) Water Jet cutting and b) Abrasive Water Jet cutting, c)Abrasive Suspension Water Jet:1. High pressure water inlet, 2. Abrasive inlet, 3. Cutting head, 4. Water nozzle, 5. Mixing chamber, 6. Focusing tube, 7. High Speed Abrasive Water Jet, 8. Sample, 9. High Speed Water Jet, 10. Pressure vessel, 11. Wet abrasive (slurry), 12. High pressure flexible hose.

Figure 18 Mixing alternatives [20].

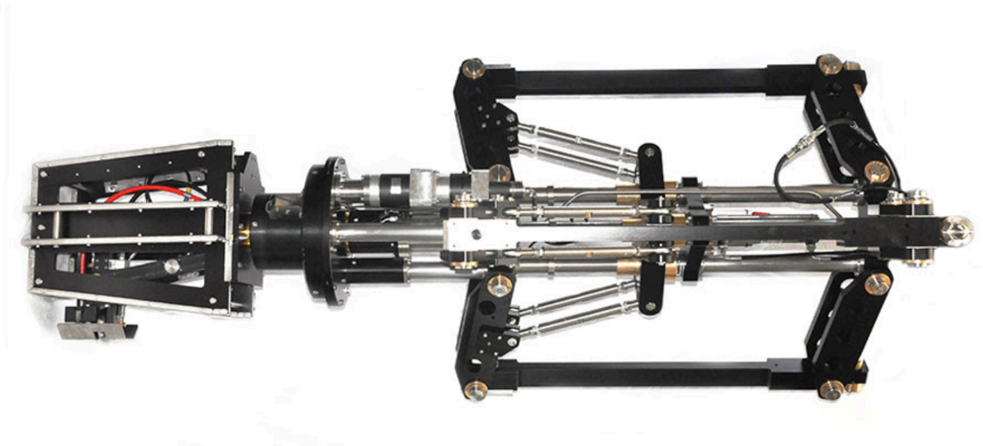

Figure 19 Downhole Cutting Heads [14].

3.1.9 Guillotine

The guillotine is using hydraulic power to push a knife against an anvil and cut e.g. cable, rope, riser or wire. Guillotine cutter can be designed as an all-round cutting tool or for a specific task e.g. nut cutter. The biggest guillotine cutter produced by Webtools can cut cables and risers/pipes up to 270mm. The cutter is powered and handled by the ROV when used subsea.

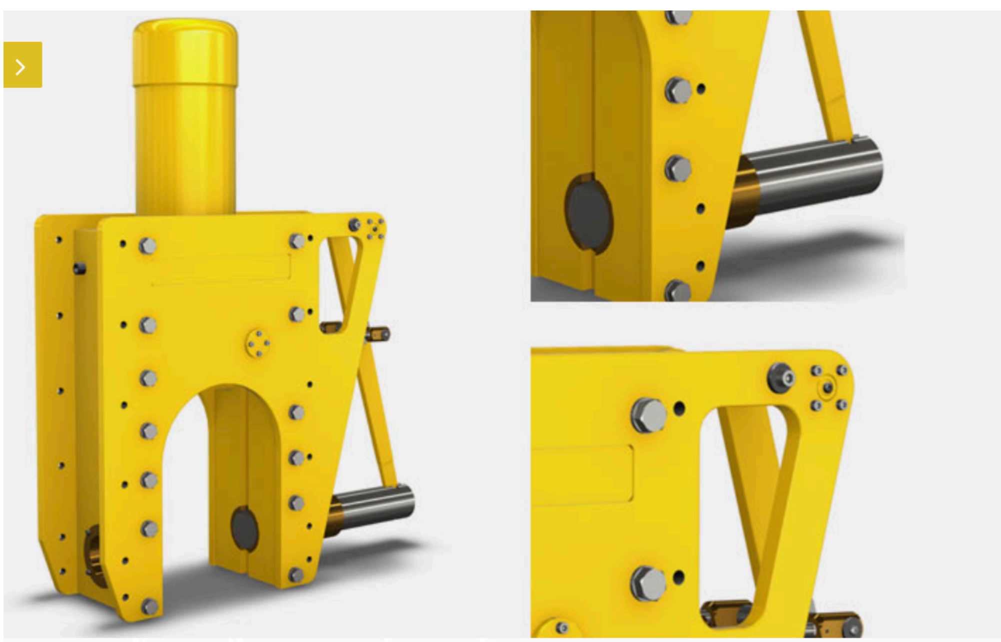

Figure 20 Guillotine [21]

Figure 21 Nut cutter [22]

3.1.10 Shear Cutter

The shear cutter uses hydraulic power to cut materials between two knives. The shear cutter is very powerful but also heavy construction. Fig 22 shows the biggest shear cutter from UCS. The cutting force is 1650 tonnes and cutting capacity is Ø610mm [23]. The shear cutter can be used both over and under water, but it must be handled by crane. The weight in air is 9,5 tonnes and the length are over 4 meters.

Figure 22 Shear cutter [23].

3.1.11 Explosives

An explosion is a very rapid exothermic chemical reaction where the explosive material is converted to very hot, dense, high-pressure gas. The gas from the explosion expands at a very high velocity to reach equilibrium with the surroundings. This rapidly expanding gas creates a shockwave that can be used in decommissioning.

Explosives are widely used in the Gulf of Mexico in decommissioning of offshore oil platforms and are recognized as a safe and effective method [24]. Explosives are a very effective method to cut piles under the mudline, the piles are dredged out and explosives are placed inside, the shockwave of expanding gas cut the pile. Figure 22 shows explosives in different arrangements.

The shockwave also has the potential to harm or kill fish and animals (including humans) in the vicinity. To minimize this hazard, the rules and regulations for the use of explosives must be followed.

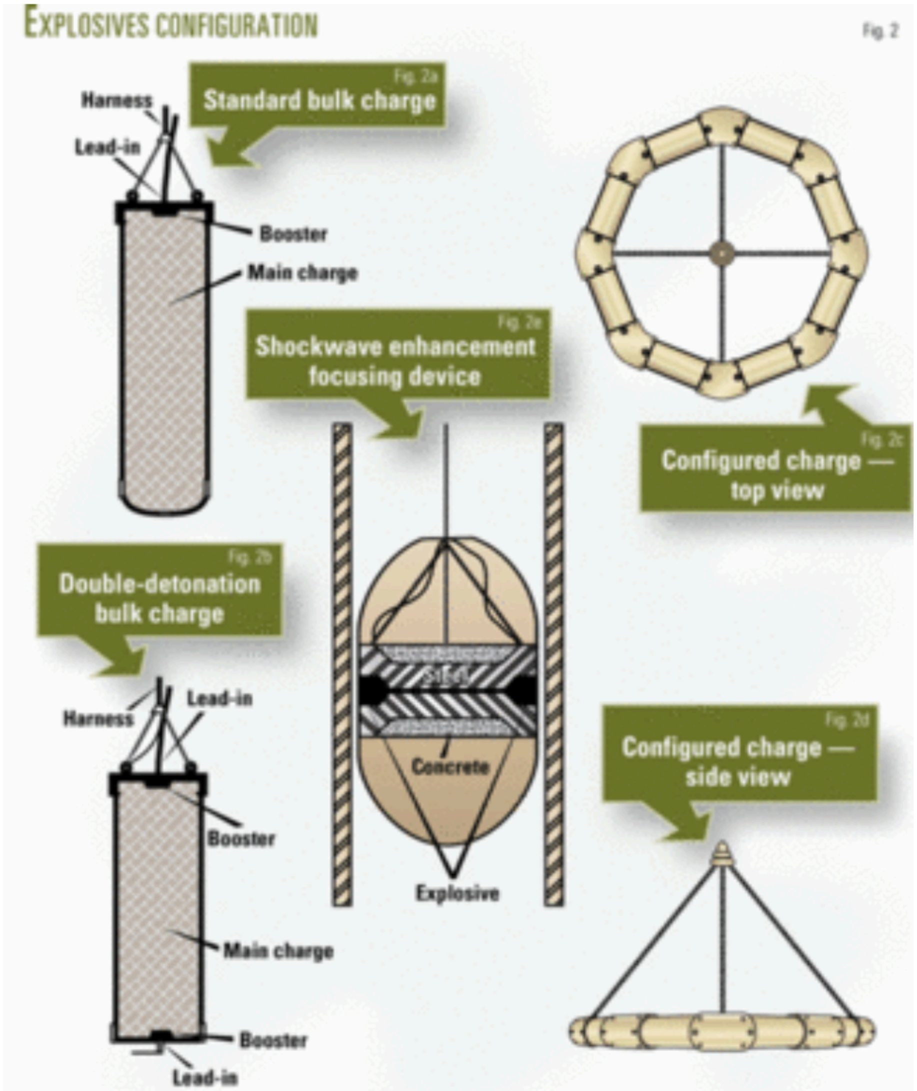

Figure 23 Explosives configuration [25]

3.2 DeepOcean experiences from oil/gas decom

This chapter describes the experience DeepOcean have with different cutting tools and how DeepOcean choose cutting tools, MOM can be found in Appendix 9.2

DeepOcean is a worldwide subsea service provider to the oil and gas industry. The company has been involved in some small decommissioning work in the oil & gas industry and considers this to be marked in the future. The company has not been involved in offshore wind farm installation, only cable work e.g. cable laying, trenching and connection. They have used subsea cutting both during service work and decommissioning work. They have used different cutting tools such as the guillotine, diamond wire saw, and diamond blade but mostly diamond wire saw. Total cost, SoW, and material to be cut determines the method chosen. The total cost depends on; cost for tools, mobilization cost, operation cost. Typical SoW factors are; how accessible the cutting area is and how many cuts to be performed. The need for dredging to gain access to the cut area can be a cost driver, DeepOcean estimated dredging time to be 4-5 days for the outside cut of monopile two meters below the seabed. Many equal cuts can justify a fast but expensive cutting tool. For some cut, there is only one practical solution, e.g. internal cut of the casing using high pressure water jet with abrasives for P&A (Plug and Abandon) of wells.

DeepOcean experience with different tools:

- Diamond wire saw – Relatively slow, but reliable. Easy setup and mobilization, don't need extra personnel to operate it.
- Diamond saw – Fast, more durable. Easy setup and mobilization, don't need extra personnel to operate it.
- HP water jet - Fast, but advanced mobilization/installation due to bigger team and more equipment topside. Additionally, uncertain if the cut is successful and has cut through the material.

3.3 Reach Subsea experiences from oil/gas decommissioning

This chapter describes the experience Reach Subsea has with different cutting tools used and how Reach Subsea chooses cutting tools for service and decommissioning work. MOM can be found in Appendix 9.3

Reach Subsea is a worldwide provider of IMR, ROV, Survey, Construction Support and Decommissioning Services to the oil and gas industry. The company has been involved in decommissioning work in both the oil & gas industry and the offshore wind industry. Decommissioning is a small part of the work the company is involved in, but they expect this to be a bigger part in the future.

This company has used many cutting methods, depending on the scope of work. Diamond wire, scissor cutting, guillotine, and abrasive water jet have all been used. The company has the same experience as DeepOcean with the different cutting tools/-methods.

Reach Subsea rely on diamond wire cutting, as a standard method. This is always the go-to method if possible. A reliable and simple method, both subsea and top-side. Diamond wire is easy to set up and when doing the mobilization of the vessel. It does not need a third party/technical operator!

HILTI is expanding and entering the subsea cutting market – with a diamond wire cutting technique that is double the speed as today.

The use of dredging before cutting is always a challenge, the soil can fill the trench and you never know how much time you will use.

3.4 Kværner experiences from oil/gas decom

Kværner is an international knowledge-based company with headquarter in Oslo, Norway.

Kværner is involved in the whole value chain in the oil & gas industry from executing engineering, procurement, construction (EPC) and decommissioning.

The Decom Tools project team was visiting the demolition site at Eldøyane, Stord, Norway. Kværner has been involved in decommissioning projects since 1995 with different roles in the prosses, from sub-contractor to the main contractor.

The main takeaway from the visit is:

Structures have been towed to the site floating, both floating on its own and with the use of an extra buoyancy tank.

Structures have been lifted on to barges and from barges to shore sites using HLV (Heavy Lift Vessel).

There are two main cutting methods used onshore, handheld plasma cutting and hydraulic activated shear cutter mounted on an excavator. Kværner is working with the development of more automated cutting processes, the main reason for this is safety and working environment. Working with handheld equipment on big structures takes time and the operator doesn't see the end of the job, this is a situation where the operator gets bored. Bored operators are not focused on the job and this can lead to dangerous situations and incidents. They have now, as a part of this work, mounted a guillotine cutter that cut big pieces of steel, with a thickness up to 150 mm, into small pieces ready to ship to customers.

Explosives are not recommended, there are too many uncertainties and it is only used if there is no other option. Some of the uncertainties are steel quality and amount of explosive, safety for operators and restriction on transport. If the construction doesn't fall or explosives don't explode it requires heavy safety measures before entering the area.

3.5 AF Decom experiences from oil/gas decommissioning

AF Decom is a part of the AF Gruppen which is a contracting and industrial group. AF Decom is the decommissioning part of the group and has specialized in decommissioning of offshore structures, both as the main-contractor and sub-contractor. The headquarter and demolition site is located at Raunes, Vats, approximately 40 kilometres from Haugesund. The site has 180 meters of quay with a depth of 23 meters, this allows heavy lift vessels to dock and deliver modules directly on the quay. This and the easy access with good shelter from the North-sea are the big advantages for the site.

The main takeaway from the visit is:

Decommissioning offshore is done as a reversed installation. Old platforms are built module based and are decommissioned module for module. New platforms are installed in one module and is lifted away in one lift.

AF Decom is using shear cutters and oxy-fuel cutting to cut steel on the demolition site at Raunes. Hand-held oxy-propane is used for steel cutting, this is found to be the safest and most cost-effective manually cutting method. When they can, shear cutter mounted on excavators is used to cut the modules into smaller pieces. The modules are cut into smaller pieces that fit into the combinate press and shear cutter that cut the steel into pieces ready for shipment to customers.

AF Gruppen has personnel with long experience in the use of explosives in demolition projects. AF Decom is planning to use explosives on one future project for the toppling of the structure, it is expensive to use but the operators stay away from structures that can be unstable.

AF Decom is looking into a more automated cutting solution to protect and keep the operators at a safe distance from moving objects. For the same reason they are testing other cutting methods, e.g. diamond wire cutting which doesn't create dangerous gasses that affect the operators and the local environment.

3.6 Project Workshop

The Decom Tools project arranged a workshop in Haugesund 26.04.2019, the invitation to participate was sent to companies in the industry, public administration, students and others with interest in the field and there were participants from all groups. This was also a start-up meeting with an invitation to the industry for participating in the project.

The Decom Tools project was presented for the participants and the questionnaire was discussed in plenum. The questionnaire was the same used in the excursion and workshop with companies in the oil & gas industry.

The aim of the workshop is to create a forum for cooperation and sharing of experience to develop realistic solutions to problems regarding offshore wind turbine decommissioning.

3.7 Choice of cutting tools/-methods

There are many parameters that has to be consider when the choice of cutting tools/-methods for a project is done.

Somme of the parameter are;

- Cutting speed
- Availability of tools
- Deck space available
- Cabin available for operators
- Total cost per cut
- Personal experience and preference with different tools

The considerations are different if there are one single cut or many similar cuts. With one cut the cutting speed is not important, easy setup is more important. With many similar cuts, cutting speed is more important and a complex setup with extra operators can be justified. Total cost of cut is a result of rental cost, mobilization/demobilization cost, cutting speed, cost of spare parts and personnel.

The tools are often rental tools and availability must be considered when the plans are made.

Personal experience with and preference to different tools will to some degree determine choice of tools. Table 4 shows pros and cons for cutting tools/-methods used in oil and gas industry, this is parameter that can be used when choosing cutting tools/-methods.

Cutting method	Principle	Pros	Cons
Saw	A circular or straight blade with teeth removes material.	Wide range of blades can cut almost everything. Easy setup.	Relatively slow.
Diamond wire saw	Wire with diamond segment are dragged over/trough the object being cut and remove material.	Easy setup. Doesn't need extra operators or deck space. Can cut everything softer than diamond. Fine straight cut.	Must start from scratch if wire snap in middle of cut. Relatively slow.
Oxy-fuel	Using fuel-gas and pure oxygen to oxidize the metal in an exothermic reaction.	Cost effective. High cutting speed.	Need experienced operators or automated system for fine cut. Can cut only low carbon steel and low alloy.
Laser	Using a focused laser beam to heat the metal, the heated metal is either blown away with air or N_2 or oxidized with the use of pure Oxygen.	Can cut materials not possible to cut with oxy-fuel. Can cut complex patterns. Small area affected by heat. No wear out of cutting equipment.	Not developed enough for subsea operations.
Plasma	Using heat from gas in the plasma state to melt and vaporize the electrically-conductive material.	Can cut all electrically-conductive material and materials not possible to cut with oxy-fuel. Can use clean air as gas.	Rough cut with handheld equipment.
Grinding	Friction from a circulating blade scratches away material, both the blade and material are scratched away.	Simple construction. Same tool can be used with different blade.	Used in small cut operation Slow speed. Used for maintenance.
Water jet	Using high-pressure water with abrasives to cut materials.	Is a very versatile and effective process and can cut through almost any material. Can cut thick materials, up to 1500mm concrete.	Need dedicated operators and deck space. Orifice wear out. Uncertainty regarding cut verification.
Guillotine/	Using hydraulic power to push a knife against an anvil. Use hydraulic power to cut materials between two knives.	Effective. Can be used as safety release device.	Deformation of the object being cut.
Shear-cutter	Use hydraulic power to cut materials between two knives.		
Explosives	An explosion is a very rapid exothermic chemical reaction where the explosive material is converted to very hot, dense, high-pressure gas that can cut through materials.	Effective, can blow away everything. Effective and safe on big structures.	Dangerous if used wrong. Transport with strict safety measures.

Table 4 Summary of cutting tools/-methods.

4 Alternative cutting method

This chapter will see if tools used in the oil & gas industry, experience from visited Company, and experience in the Decom tools team can be used to find alternative and more efficient cutting tools/-methods.

The aim of the Decom tool`s project is to;

Reduce the decommissioning cost by 20% and reduce the environmental footprint by 25% (Measured in CO2 equivalents).

The base case for calculation of reduction in environmental footprint and cost is reverse installation of offshore wind turbines. Cost and environmental footprint for reverse installation of offshore wind turbines is not yet calculated and defined by the Decom tool`s project. This paper use Sheringham Shoal wind park and the decommissioning paper provided by Equinor as base case.

Vessel days is the main cost driver and by reducing vessel days, both cost and environmental footprint are reduced. To achieve this, one of the solutions is to use/-develop efficient cutting tools/-methods in order to reduce the total working days for vessels involved in the operations.

The decommissioning process is presented in chapter 2.1.2.

4.1 Cutting methods 1st Campaign

Cutting requirements 1st Campaign	**Cutting solution Decom document**	**Alternative cutting solution**
Bolts	Grinder	
	Plasma cutter	
		Nut splitter
		Saw
Cable and wire	Not specified	
		Guillotine
		Pliers/Scissors
		Saw

Table 5 Alternative cutting solution 1st Campaign

The 1st Campaign is a preparation campaign and the cutting requirement is cutting of power cables, both internal cables and export cables to other wind turbines. There is always a possibility that bolts are rusty and don’t get loose with normal tools and cutting tools must be available.

Table 5 shows the cutting tools described in the decommissioning document and alternative methods during the 1st Campaign.

4.2 Cutting methods 2nd Campaign

Cutting requirement 2nd Campaign	**Cutting solution Decom document**	**Alternative cutting solution**
Bolts	Grinder	
	Plasma cutter	
		Nut splitter
		Saw
Turbine blade	Not required	
		Saw or Guillotine mounted on blade lifting arrangement.
Foundation upper cut	Plasma cutter mounted on rails for automated cutting	
		Not required
Boat landing	Not specified	Not required
Foundation lower cut	Abrasive water jet mounted on ICM for automated cutting	
		Diamond wire saw
J-tubes	Diamond Wire saw	
		Not required

Table 6 Alternative cutting solutions 2nd Campaign

4.2.1 Alternative method wind turbine removal

Decommissioning of the wind turbine is planned as a reversed installation with operators inside the wind turbine to loosen bolts and nuts. The operator is also a preparing lifting arrangement and hook up the crane. To save vessel days an alternative method for decommissioning of turbine blades can be considered.

The decommissioning method is to cut the turbine blade with saw or guillotine which is mounted on the turbine blade lifting arrangement. Figure 24 shows the principles of lifting arrangement with cutting tool.

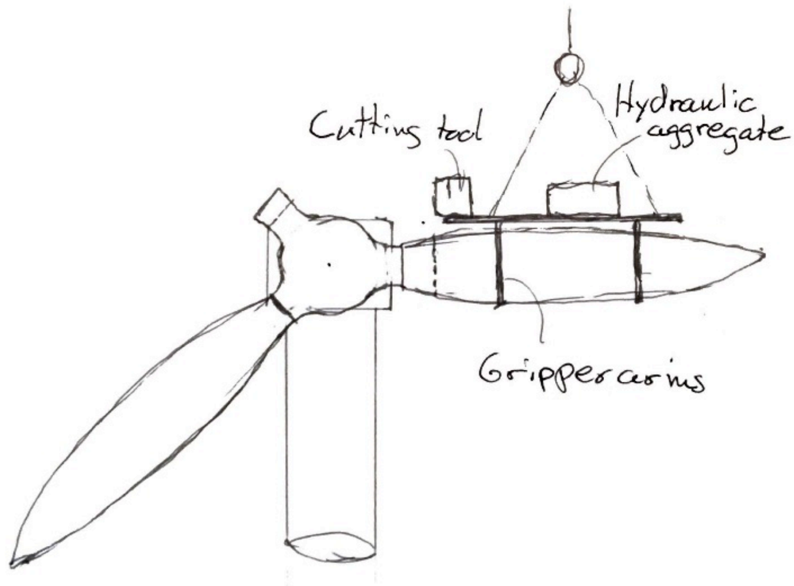

Figure 24 Wind turbine blade cutting tool

4.2.2 Alternative method foundation removal

The experience from DeepOcean and Reach Subsea is;

Both DeepOcean and Reach Subsea preferred diamond wire saw if they can choose, it is reliable and easy to set up. The alternative method should be to use a diamond wire saw, this choice results in an outside cut. An outside cut of monopile two meters below seabed requires dredging of the seabed around the monopile to get access to the cutting point. Figure 25 shows dredging area for outside cut of monopile.

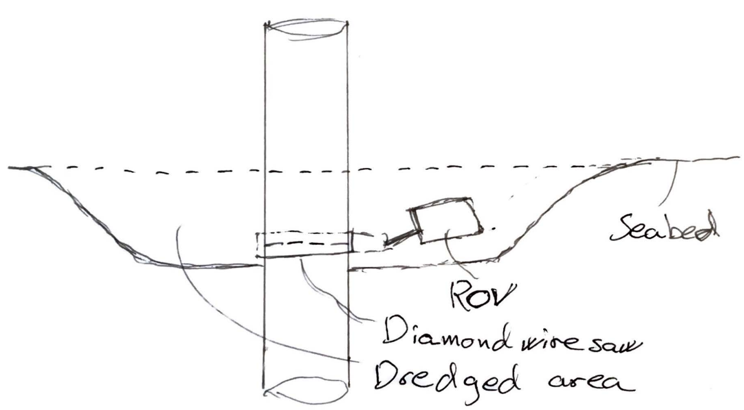

Figure 25 Dredging area required with outside cut of monopile

DeepOcean and Reach Subsea both have the same experience related to dredging, it is an uncertainty in the operation, and it is difficult to estimate dredging time. The challenge is to find a solution that uses a diamond wire saw without dredging, the cut must then be performed over the seabed.

The solution can be found in the monopile installation prosses, the monopile is driven down in the seabed with the use of a hydraulic hammer.

The new decommissioning method is taking the experience with the diamond wire saw and dredging into account and combine these two factors in a new method. The foundation is cut with diamond wire saw above the seabed, the rest of the monopile is driven further down in the seabed with a hydraulic or vibrating hammer. Figure 26 shows the process step by step.

The operation can be done as a step by step operation;

- The diamond wire saw is lowered into position with the vessel crane or ROV.
- Foundation is supported by the vessel crane during the cut and lifted away.
- Hydraulic or vibrating hammer is placed on the remaining monopile and it is driven into the seabed.

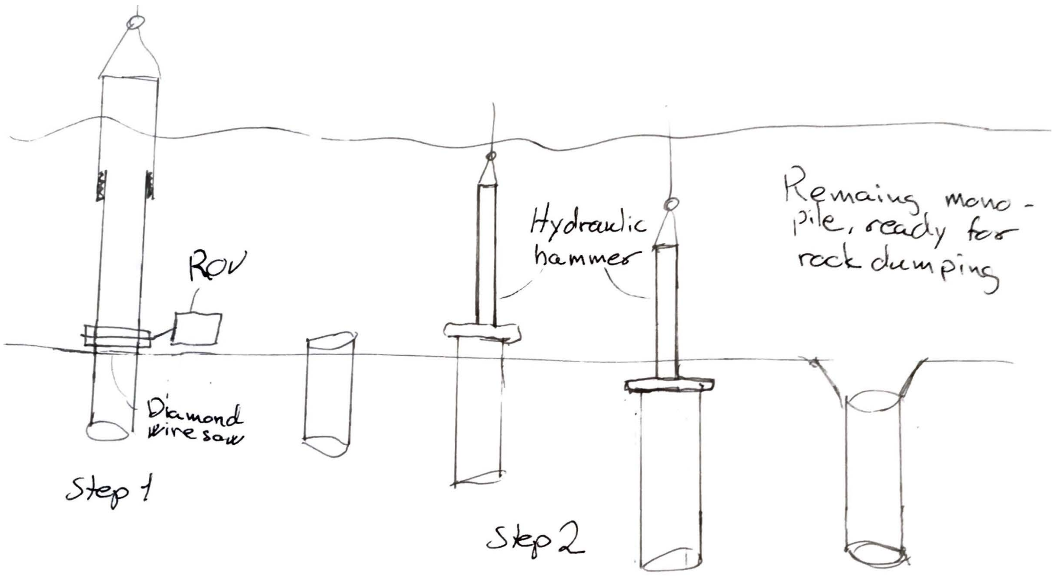

Figure 26 Foundation decommissioning process

The operation can, with the construction of a new tool, be done in one operation. The tool combines, and has integrated lifting gear, hydraulic hammer, diamond wire saw and support pin for the monopile. Figure 27 shows the tool and 28 shows step by step operation.

Approximately size and weight of tool;

The Menck MHU 3500S Hydraulic hammer is chosen as the hydraulic hammer in the tool, this is according to Menck the world's most powerful hydraulic hammer, the hammer weight 310 tonnes and is approximately 20 meters long. When used on a pile, the hammer is equipped with a pile sleeve with a weight of 113 tonnes and a length of 5 meters. [26]

The total size and weight for the hydraulic hammer w/pile sleeve will be used as size and weight for topside arrangement on the tool. In addition, the weight of support pin arrangement and diamond wire saw is estimated. The total estimated weight and size for the tool are 500 tonnes and 25 meters high.

The working sequence for the operation when using the new tool is;

- The tool is placed on top of the foundation by vessel crane, using flange on the foundation to lock the tool to the foundation
- The diamond wire saw is lowered into position.
- Clamp with support pin is placed right over the cutting area
- The support pin is extracted behind the cutting wire to hold the monopile in position
- The diamond wire saw is recovered to the tool.
- Hydraulic hammer drives the rest of the monopile further down in seabed.
- Foundation is lifted onboard and the site is ready for rock dumping.

When using the new tool, the foundation removal can be done in one operation, this is cost effective and safe. The site is left ready for the 3rd Campaign which is rock dumping and survey.

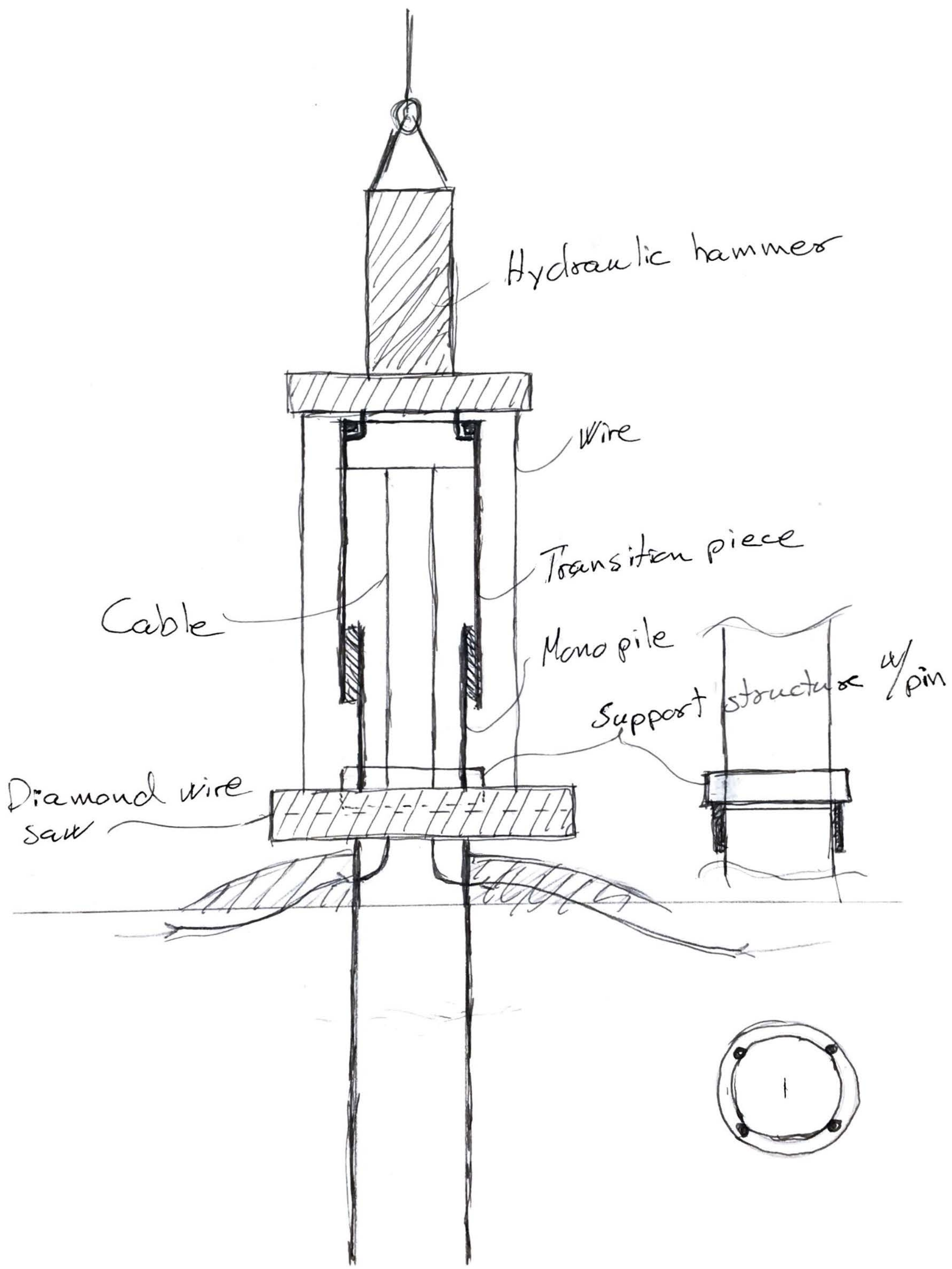

Figure 27 Tool for decommissioning of offshore wind turbine foundation.

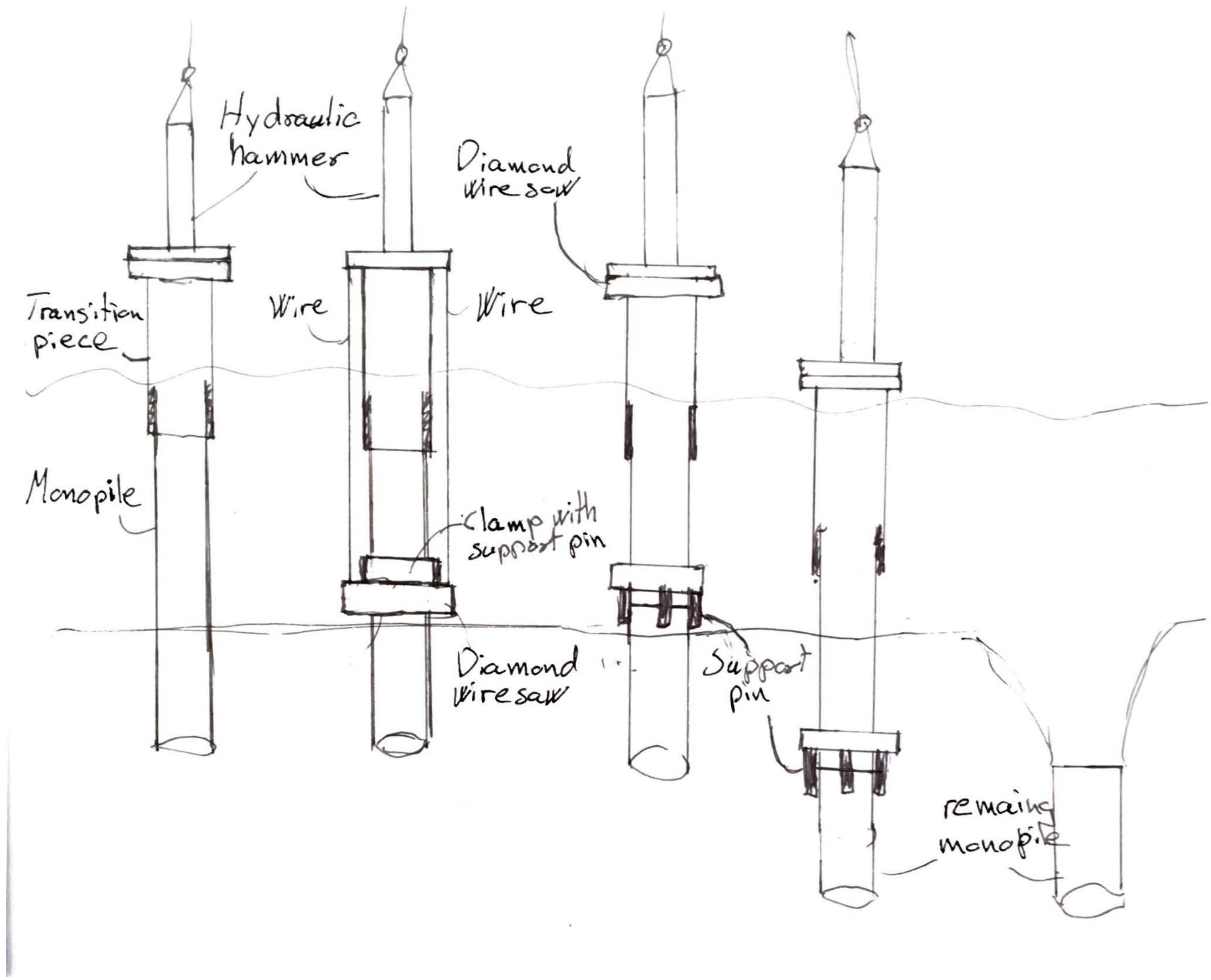

Figure 28 Wind turbine foundation decommissioning

5 Discussion

This chapter discusses if the improvements presented in chapter 4. are possible, safer and more efficient than decommissioning method presented in the decommissioning document made by Equinor.

5.1 1st Campaign

The SoW for the 1st Campaign is to prepare the wind turbine for decommissioning, this is done by a small team of operators entering the wind turbine from PTVs. The team will prepare the wind turbine to secure efficient use of heavy lifting vessel. To secure this, everything that can be done in advance must be done, including;

- Clear the wind turbine for loose items
- Bolts are prepared with cleaning and application of penetrating oil.
- Cutting cables at the separation point.
- Installation of temporary lightning
- Installation of power supply for the high-speed turbine turning the motor.
- Remove the elevator from the tower.

The cutting requirement in this campaign is cutting of cables and wire, it can additionally be some bolts that need to be cut. Safety for the operators is the main criterion when choosing a cutting tool. The use of grinder and plasma cutter creates dust and gasses, the use of saw and guillotine creates less dust and gasses and is a better alternative.

By using the alternative method, there is no need for entering the airtight and oxygen-free space in the transition piece for installing ventilation. Entering oxygen free and confined spaces is a dangerous operation and if possible, should be avoided. Before entering, space must be ventilated, and gas content must be measured to secure a safe atmosphere. The alternative method is safer for the operators, save time and total cost for decommissioning.

5.2 2nd Campaign

The SoW for the 2nd Campaign is the most demanding and time-consuming in the decommissioning of the wind turbine. This is also the part where the new approach has the potential for a considerable cut in vessel time and decommissioning cost The SoW for the Campaign is to remove the wind turbine with foundation down to two meters below the seabed and make the site ready for the 3rd Campaign which is rock dumping and survey.

5.2.1 Discussion, alternative method wind turbine removal

There are different alternatives to decommissioning of turbine blades.

- Remove all and let the hub stay on the generator.
- Remove the hub with blades
- Remove one or two blades

The alternative method presented in chapter 4 is to cut blades near the hub and let the rest of the blades and hub stay on the generator.

Cutting equipment is mounted on blade lifting rig, powered and controlled from the jack-up vessel. This equipment will increase the weight of the lifting rig, this will not be a problem, the vessel used in this operation is also lifting nacelle and tower with a weight of 140 and 300 tonnes, respectively. The blades weight 20 tonnes each, the rest of the crane capacity can be used to construct lifting rig includes cutting device. The increased weight can also stabilize the lifting rig in windy conditions and expand the weather window for the lifting operation.

The blades are made from composite material and can be cut with saw or guillotine. Debris from the cutting process can be a safety and environmental issue and collection equipment must be considered when constructing the cutting tool. The variables for choosing the cutting tool are reliability, amount of debris and cutting speed.

A guillotine is reliable and has high cutting speed, the drawback is uncertainty regarding the amount of debris. The guillotine is pushing a knife through the blade, this can make the blade crack in pieces around the cutting area, this is something that can be difficult to control.

A saw is reliable, and the amount of debris is known and can be collected. Cutting speed depends on the construction and principles of saw used e.g. diamond wire or blade. One drawback for the method is the reliability of the saw and how to deal with a breakdown of the saw during the cutting prosses. This can create a potentially dangerous situation depending on were in the cutting prosses the saw fail. If the saw fails, the lifting rig must be recovered to deck for repair, the turbine blade is partly cut, and the blade construction integrity is destroyed. This can be a very dangerous situation with the vessel locked to the wind turbine, and risk of falling objects (turbine blade) if recovering of lifting rig. This situation is so critical that the benefits of the blade cutting method are outweighed by the risk of setting the vessel in a dangerous situation.

The nacelle is bolted to the tower on an internal flange, decommissioning is planned as a reverse installation, loosen the bolts and lift the nacelle of the tower. The tower is in two parts and is planned to take it down in two separate lifts. Bolts and nuts not possible to remove with the conventional method will be cut off using saw or nut splitter, this method creates less gas than plasma cutter and grinder in the tower when used. The use of nut splitter and saw also minimize risk for fire in the working area.

The choice of decommissioning method is always guided by the best possible safety for the operator, environment and at the end best possible economy. The use of nut splitter and saw creates less gas and is a safer alternative for the operators. The time difference between the methods is negligible, there are very few bolts that need cutting. The use of the blade cutting method has the potential to create a very dangerous and complex situation and is not recommended.

5.2.2 Discussion, alternative method foundation removal

Decommissioning of the foundation is in the decommissioning document written by Equinor planned with standard equipment, tools, and methods known from the oil & gas industry.
The decommissioning process can be described as follow;

- Two cuts of monopile/transition piece.
- People in transition piece (enclosed space) for mounting of plasma cutter and cutting of cables.
- Use of divers inside the foundation to cut j-tubes at the exit point. This is planned without the use of a dedicated diving boat, at the same time as lifting operations.
- An additional cut of boat landing outside on transition piece.
- Many lifts; transition piece, 2 X j-tubes, monopile.
- Cables may be lifted when lifting monopile.

The alternative method is an innovative method with the following benefit;

- One cut of foundation, including j-tubes
- One lift with transition piece, monopile, and j-tubes
- The site is ready for rock dumping with one operation.
- One tool with one cutting tool, hydraulic hammer, and lifting equipment.

- No people in the foundation. Health and safety issues.
- No divers. Health and safety issues.
- No dredging. Environmental issue.
- Cables remain buried. Environmental issue.

The method in the decommissioning document is composed of well-known sub-operations. This is a strength for the method, the operators know how to do it and know it will work. The operation is planned as a step by step operation where the operators have responsibility for one sub-operation at the time. There are several teams in action at the same time, all well trained in their specific work tasks. Several teams in action at the same time is a challenge for the safety for the operators. Lifting operations, work inside foundation and diving operation inside the foundation is planned to be performed at the same time. This is not a good solution with many operators at the same and the risk for an incident increase.

The alternative method relies on one tool, this tool is composed of well-known technology but have never been combined in one tool. This can be a drawback for the method if one of the tools fails, the operation fails. The cutting operation is critical, the foundation can be unstable if the diamond wire saw fail during the cut and recovering of the tool to deck for repair is impossible. In this scenario it is not possible to abort the operation with safe recovering of tool and/or foundation, the vessel is connected and must support the foundation until the situation is solved. One alternative in this situation is to recover the diamond wire saw to surface and repair the diamond wire saw in the upper position on the tool. If the foundation is unstable and must be supported by the crane, this is not a safe solution. The vessel can disconnect the tool from the foundation at any time without danger for the vessel, but it can create a complex recovery prosses for the foundation removal process.
The solution is then to use a separate diamond wire saw to cut the foundation. Diamond wire saw is a reliable and robust construction that subsea company has good experience with and trust on, this scenario can nevertheless occur and must be a part of the plan.

The main uncertainty for the method is the grouted connection between the transition piece and monopile, this connection has to withstand and transfer forces from the hydraulic hammer to the monopile. The transition piece and monopile must be held in place after the cut, the forces from the hydraulic hammer are transferred from the transition piece and monopile to the remaining monopile. To hold the transition piece and monopile in position the cutting tool is equipped with a clamp with support pin, the clamp is mounted on the monopile above the cut. Support pins are extracted behind the diamond wire and will hold the transition piece and monopile in position over the remaining monopile.

The pins have to withstand horizontal forces from the sea, these forces will define and restrict the operational weather window for the operation. The forces from the sea must be calculated and weather limitations must be defined before the operation starts. The calculation can be done with the simulation and analysis tool Sesam from DNV-GL, OrcaFlex or similar software program developed for this purpose.

To eliminate the uncertainty with the grouted connection, the method can be performed in two steps or campaign. First step; cut the foundation with diamond wire saw and lift onboard the transition piece and monopile. Second step; The remaining monopile is driven down with hydraulic or vibrating hammer.

By splitting the operations into two operations it can be performed with standard equipment.

Standard equipment is;

- Transition piece lifting tool to connect vessel crane to the foundation
- Diamond wire saw for cutting of foundation
- Hydraulic or vibrating hammer to drive the remaining monopile down in seabed.

Using standard equipment and separate the operation in two campaigns, the operation has more flexibility regarding vessel size and type. There are more vessels available that are suitable for the operations, and the vessels can be optimized for each campaign.

Crane capacity is the sum of the weight of transition piece, half of the monopile, grout, foundation and lifting gear. The maximum weight can be approximately 600 tonnes. Weight must be calculated using data from the installation and fabrication process.

The foundation removal campaign saves approx. 500 tonnes crane capacity and 25 meters lifting height not using the combinate tool. Minimum crane capacity using the combinate tool is 1100 tonnes, it is likely that the operation must be performed by a jack-up vessel to have sufficient crane capacity. Performing the operation in two campaign using standard methods eliminate the need for jack-up vessel and make it possible to use offshore vessel with DP (Dynamic Positioning) and lower crane capacity.

The second campaign, driving the remaining monopile down in seabed can be performed using offshore vessel with DP and crane. The crane operation in this campaign is restricted to lift the hydraulic hammer in position on the remaining monopile, the weight of the hydraulic hammer determines crane capacity.

More flexibility regarding vessel size and type will increase the number of contractors able to perform the operation, this increases the competition and lowers the price for the work.

When the method is separated into two campaigns, the operational weather window is easier to determine and handle. The operational weather window is determined from vessel and crane characteristics. Typical vessel characteristics are the size and DP capability. If the vessel crane is equipped with active heave compensation, the vessel can work in rougher condition. If the operational plan requires the use of ROV, launch, and recovery is an important weather criterion.

Regardless if the method is performed in one or two operations, the remaining monopile is driven further down in seabed. This presupposes that it is possible to separate the remaining monopile from the soil. When Lely offshore wind park was decommissioned, the monopile was separated from the soil and extracted from the seabed using a vibrating hammer. The monopile was smaller than the one on Sheringham Shoal Offshore Wind Farm, but this shows that it is possible to separate the monopile from the soil after many years.

Appendix B. Distribution of soil units vs. Turbine locations shows survey result down to 55 meters below the sea surface and there is no bedrock present. The length of the monopile is 44-66 meters, for the monopile longer than 55 meters, the survey data for the location must be consulted for bedrock. Data from the installation process can also be consulted for data about soil, resistance in the soil and forces needed to drive the monopile down in seabed for each location. There can be some of the monopile that is difficult to drive further down in the seabed. They can still be cut at the same spot, this will create easy access to the inside of the monopile for internal dredging and cutting.

6 Conclusion

The aim of the project is to reduce the decommissioning cost by 20% and the environmental footprint by 25% (measured in CO2 equivalents). The aim for the master thesis is to use experience with cutting tools/-methods from offshore oil and gas industry, see if the tools/-methods are suitable for use during decommissioning of offshore wind farms and suggest new/-modified cutting tools/-methods.

The experience is gathered from local companies working in the oil & gas industry and their experience is used to suggest two new tool/-method.

The environmental footprint and cost used in the Decom tools project is reverse installation of wind turbines, this is not yet calculated. I can therefore only assume that my method will contribute to a reduction in cost and environmental footprint. The reason for my assumption is that the new tool/-method is simpler, faster, safer and has fewer operators in action.

Sheringham Shoal wind park is used as a base case and the method presented in the decommissioning document provided by Equinor is compared with my tools/-methods. The main advantage of my decommissioning process is the safety aspect, the process eliminates several potentially dangerous operations and reduce the total number of operations.

The blade cutting tool/-method reduces the number of manual operations in the nacelle, this factor alone increases the safety for the operators working in the tower. The use of the blade cutting method has the potential to create a very dangerous and complex situation for vessel and operators if the saw fails and is not recommended.

The foundation removal method can be done with one tool, but the tool is not constructed, and it is more reliable to divide the method into two campaigns using standard tools.

The offshore wind turbine decommissioning process can be divided into several campaigns and the vessel can be optimized for each campaign, this can reduce the cost and environmental footprint even more. The decommissioning process presented in this paper is, compared with the process presented by Equinor, an operation with fewer people in action and less chance for damage to health, safety, and environment.

7 Further work

This paper has presented new tools/-methods for decommissioning of offshore wind turbines. There are two new approaches that can be used for decommissioning of offshore wind turbines, blade cutting, and foundation decommissioning tool/-method.

The cutting method used for blade cutting is not specified. Further work is needed to determine which cutting method is best suited regarding cutting speed and amount of debris. Analysis of the reliability of the chosen cutting method and how to deal with failure must be a part of this work.

In the foundation decommissioning tool/-method, wire diamond wire saw is used, this is based on experience from the company visited. Diamond wire saw has its disadvantages, e.g. if the wire snap, the tool must be recovered, fixed and the cutting prosses must be started from scratch. Maybe other cutting methods can be considered. Water cutting with abrasive and cut verification has had a great development in the latest years. This is something that could be of interest and should be investigated.

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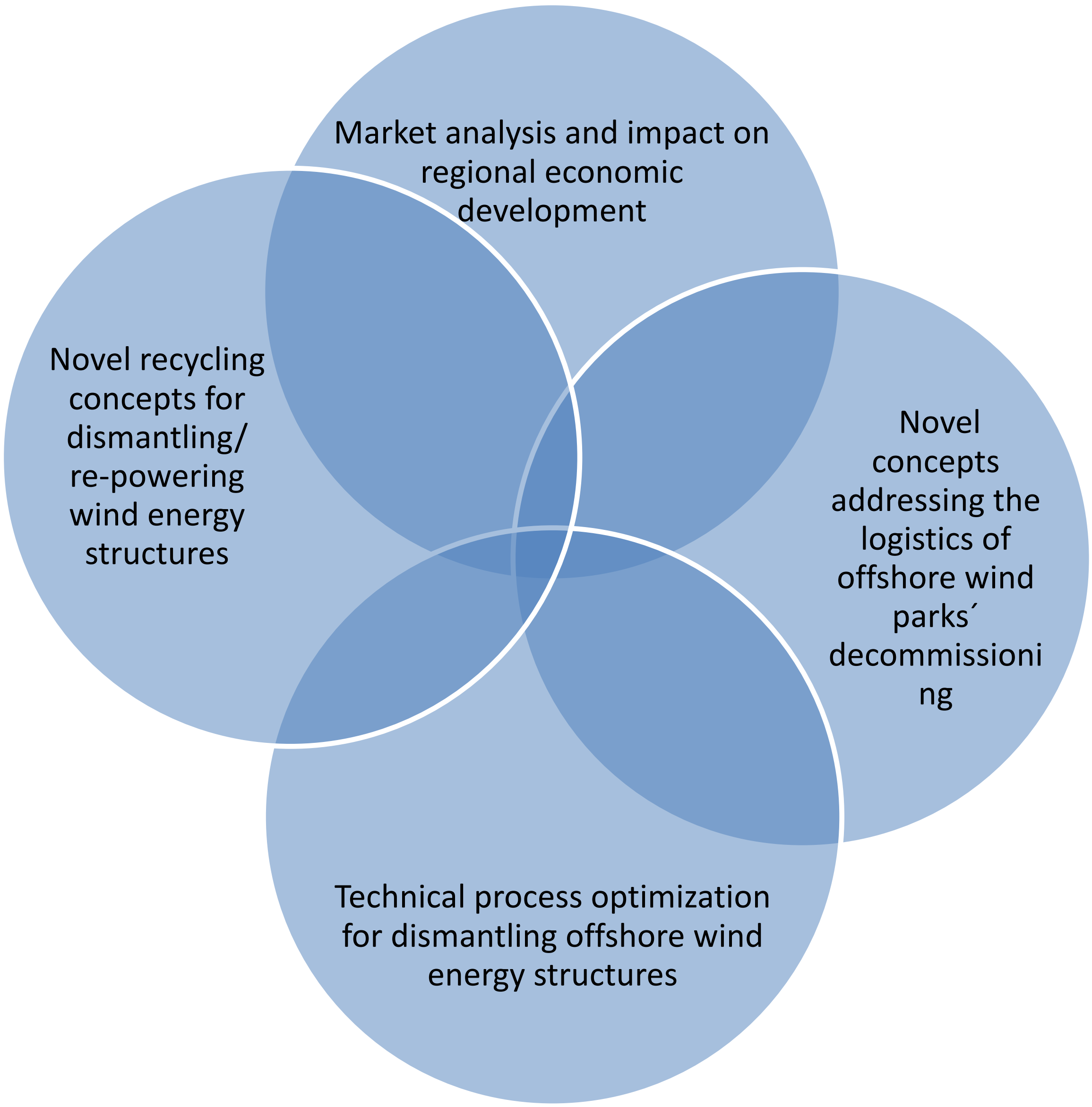
Appendix

Appendix A. INTERREG NORTH SEA REGION Programme (EU-prosjekt)

"Decommissioning" of offshore windfarms (DecomTools)

Detailed project objectives:

- ✓ Process optimization for dismantling offshore wind energy structures
- ✓ Developing new logistical concepts for dismantling offshore wind structures
- ✓ Develop new recycling concept for dismantling / re-powering offshore wind energy structures
- ✓ Foster the market uptake of the newly developed


Market analysis and impact on regional economic development
Novel recycling concepts for dismantling/ re-powering wind energy structures
Novel concepts addressing the logistics of offshore wind parks´ decommissioning
Technical process optimization for dismantling offshore wind energy structures

Our "Scope":

Use the methods and experiences of "Decommissioning" of offshore installations and apply this in connection with. offshore wind farms, as well as looking at new methods and vessels.

Partnership

13 Partners from 6 North Sea Region-countries (DE, DK, BE, NL, UK and NOR) are involved: public authorities, business development agencies, businesses, scientific institutions and public infrastructure providers. Associated partners will support the project.

Partners:

1. University of Applied Sciences Emden/Leer (Lead) (DE)
2. Hamburg Institute of International Economics - HWWI (DE)
3. Maritime Cluster Fyn (DK)
4. Offshoreenergy.dk (DK)
5. Port of Grenaa (DK)
6. Samsoe Kommune (DK)

7. Port of Oostende (BE)
8. Regional Development Organisation West-Flanders, POM (BE)
9. De Lauwershorst Groep (NL)
10. Energy Valley (NL)
11. Virol (NL)
12. University of Aberdeen (UK)
13. Western Norway University of Applied Science (NOR)

Budget:

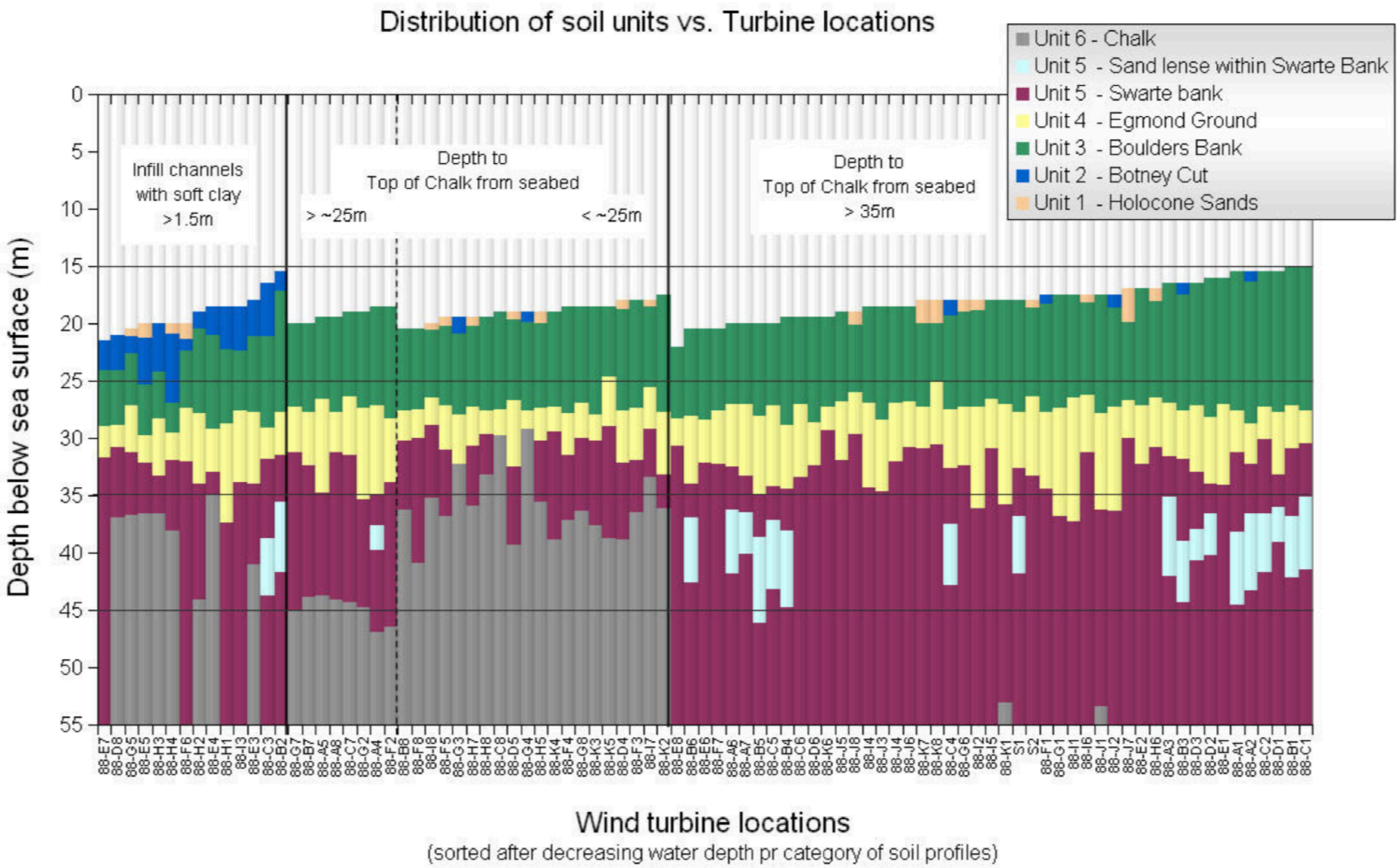
Total: 4,7 mills. Euro

HVL's share: 178.000 Euro

Schedule:

The project runs for 4 years

Appendix B. Distribution of soil units vs. Turbine locations



Appendix C. Minutes of meeting DeepOcean

Minutes of meeting DeepOcean on the 25th of January 2019.

Present:

Person 1, DeepOcean

Person 2, DeepOcean

Jens Christian Lindaas, HVL

Andres Olivares Lopez, HVL

Børre Mæland, HVL

Martin Urnes, HVL

Questions related to company visits (subsea operation- /construction companies)

- **Which decommissioning projects (oil and gas) have your company been involved in?**
  DeepOcean have been involved in many projects subsea and offshore; steel removal, two different loading buoy removals, debris removal, drill string recovery, two times wellhead decom, mattress recovery, structural removal, drill cutting, pipeline decom.
- **What has been your Scope of Work in these projects?**
  DeepOcean has done engineering, project management for the subsea operation. Operations include all types of dredging, a variety of lifting operations, cutting horizontal and vertical, cutting internal and external, pre-operation survey and post-operation survey, recovery of items into baskets and directly onto deck.
- **What methods and tools have been used for cutting/dismantling the structures (subsea and topside)?**
  DeepOcean ONLY subsea. Mostly diamond saw/diamond blade cutting. However, HP water jetting grit/abrasives also used. Guillotine cutting has also been used. Whatever method, it is ALWAYS depending on the cost, SoW and material being cut.
- **What is your experience using these methods/tools?**
  Diamond wire – relatively slow, but reliable. Easy transport/mobilization.
  Diamond saw blade – Fast, more durable.
  HP water jet – Fast, but advanced mobilization/installation due to bigger team topside. Additionally, uncertain if cut is successful.

- **How have the parts been lifted onboard the vessel(s) and transported to the onshore base?**

  Depending on the size of the pieces

  Heavy – entire structure/platform.

  Medium – Structure cut into a few pieces.

  Small – structure cut into several smaller pieces.

- **Which types of vessels have you been using?**

  Construction vessels and jack-up rigs.

- **Has towing of structure elements been used?**

  Yes, but mostly for whole structures (loading buoy). For this, usually towing vessel is acquired.

- **Which onshore bases or quay facilities have you been using for the further dismantling and recirculation process?**

  It is typical procedure to keep the elements in the country where the wind park/subsea structure is based. Alas, for floating structures the UK/German coast is not always suitable.

- **Which cutting methods and tools have they been using?**

  This is not within the scope/knowledge of the subsea/decom company.

- **Where has the material been sent for further processing/recirculation?**

  Same as previous.

- **Have you been involved in installation of offshore windmills? Which windmills/parks?**

  No, only for cable grid and export cable for a few projects.

- **What has been your Scope of Work in these projects?**

  Cable laying, dredging and connection.

- **Can the installation process be easily reversed for decommissioning of the windmills?**

  Yes, but what is most cost effective is usually a different method.

- **Will decommissioning projects related to oil and gas be a growing part of your business for the next five years?**

  Yes, they would like to be part of the “decom-wave” hopefully hitting Norway in 5-10 years.

- **Are you planning to expand your international operations related to decommissioning projects or will your main focus be in the Norwegian sector for the next five years?**

  They are involved in decom in UK. UK is already in the “decom-wave”

- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**

  Yes, if this can increase revenue.

Appendix D. Minutes of meeting Reach Subsea

DECOM Tools Project

Summary of minutes of meeting at Reach Subsea on the 22nd of February 2019.

Present:

Person 1, Reach Subsea

Person 2, Reach Subsea

Person 3, Reach Subsea

Jens Christian Lindaas, HVL

Jan Hechler, HVL

Børre Mæland, HVL

Martin Urnes, HVL

Questions related to company visits (subsea operation- /construction companies):

- **Which decommissioning projects (oil and gas) have your company been involved in?**
  Brent, removal of debris on the decom of two of the Brent field fixed platforms.
  Pile removal of Wikinger wind farm (40m depth).
  Removal of trawl protection structure and recovering of concrete subsea structures.
- **What has been your Scope of Work in these projects?**
  Brent SOW – engineering, project management and execution of the scope.
  Wikinger wind farm SOW - Removed 9 piles in the Baltic sea. Mobilized soil plug removal, dredging equipment, abrasive HP water jet.
  Trawl protection removal SOW – engineering, project management, execution and disposal of recovered items.
- **What methods and tools have been used for cutting/dismantling the structures (subsea and topside)?**
  This company has been involved with many methods, depending on the scope of work. Diamond wire, scissor cutting, guillotine and abrasive water jet have all been used.

- **What is your experience using these methods/tools?**
  This company rely on diamond wire cutting, as a standard method. This is always the go-to method if possible. Reliable and simple method, both subsea and top-side. Diamond wire is easy to set up and when doing the mobilization of vessel. Does not need third party/technical operator! HILTI is expanding and entering the subsea cutting market – with a diamond wire cutting technique that is double the speed as today. Dredging is always a cost driver and is an uncertainty in the plan, it is difficult to estimate time used.
- **How have the parts been lifted onboard the vessel(s) and transported to the onshore base?**
  This company has used subsea basket, due to simple and safe sea fastening of the gathered material.
- **Which types of vessels have you been using?**
  offshore construction vessels, IMR-vessels, PSV.
- **Has towing of structure elements been used?**
  No.
- **Which onshore bases or quay facilities have you been using for the further dismantling and recirculation process?**
  N/A.
- **Which cutting methods and tools have they been using?**
  This is not within the scope/knowledge of the subsea/decom company.
- **Where has the material been sent for further processing/recirculation?**
  Same as previous.
- **Have you been involved in installation of offshore windmills? Which windmills/parks?**
  Not for wind turbines, but for the concrete stabilization mats. And also, the packs of rock, used to lay on cables for protection. Scour protection has also been laid.
- **What has been your Scope of Work in these projects?**
  Mattress installation
- **Can the installation process be easily reversed for decommissioning of the windmills?**
  Yes, but what is most cost effective is usually a different method.
- **Will decommissioning projects related to oil and gas be a growing part of your business for the next five years?**

Yes, they would like to be part of the “decom-wave” hopefully hitting Norway in 5-10 years.

- **Are you planning to expand your international operations related to decommissioning projects or will your main focus be in the Norwegian sector for the next five years?**

  As long as they can make money, they do anything.

- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**

  Yes, if this can increase revenue.

Appendix E. Minutes of meeting Kvaerner

Minutes of meeting at Kvaerner Stord Base on the 15th of March 2019.

Person 1, Kvaerner

Person 2, Kvaerner

Person 3, Kvaerner

Person 4, Kvaerner

Jens Christian Lindaas, HVL

Andres Olivares, HVL

Børre Mæland, HVL

Martin Urnes, HVL

Questions related to company visits (subsea operation- /construction companies):

- **Which decommissioning projects (oil and gas) have your company been involved in?**
  Kvaerner have been involved in decom projects from 1995 and onwards. Reference is made to Attachment 1 Experience List.
- **What has been your Scope of Work in these projects?**
  The projects have been related to engineering and preparation for decommissioning, some projects include removal operation and most include the onshore deconstruction and disposal operations. Reference is made to Attachment 1 Experience List.
- **What methods and tools have been used for cutting /dismantling the structures (subsea and topside)?**
  Main methods used onshore are mechanical cutting by shears (mobile and stationary) and gas cutting. Some automatic cutting and semi-automatic cutting techniques and tools are used. Cold cutting like eg. diamond wire is used for certain operations.
  For offshore and inshore works the techniques for onshore are utilised above waters. Subsea water and water grit cutting technology are used as well as diamond wire, special shears etc. There are various specialised suppliers for subsea cutting tools.

There was a discussion on the use of explosives, but Kvaerner would rather use other methods if possible. This due to steel quality and uncertain method. Also, it will cause a big problem if it won't explode correctly.

- **What is your experience using these methods /tools?**

  The most efficient tools as per today are mechanical cutting by shears and gas cutting. Other tools are used tactically for specific tasks. The experience from using the different tools depend on the application and the correct tools and cutting techniques must be selected based on the structure to be cut and working conditions.

  They are working towards more automatically cutting tools.
- **How have the parts been lifted onboard the vessel(s) and transported to the onshore base?**

  Modules and structures have been lifted onboard the vessel/HLV using the vessel crane.
- **Which types of vessels have you been using?**

  Modules and structures have been lifted onboard the vessel/HLV using the vessel crane.
- **Has towing of structure elements been used?**

  Yes, eg. towing of subsea structures using pencil buoy and removing of jacket structure using buoyancy tanks.
- **Which onshore bases or quay facilities have you been using for the further dismantling and recirculation process?**

  Mainly Kvaerner's Disposal site at Eldøyane, Stord and for part of Frigg the Greenhead Base at Lerwick, Shetland.
- **Which cutting methods and tools have they been using?**

  Reference is made to question 3 above.
- **Where has the material been sent for further processing /recirculation?**

  The steel materials are cut in chargeable sizes and shipped to meltery in Europe. Stainless steel, copper, zink etc. is transported to more specialised recycling facilities. Wastes are treated, incinerated or disposed off through approved waste handling contractors.
- **Have you been involved in installation of offshore windmills? Which windmills /parks?**

  No
- **What has been your Scope of Work in these projects?**

  N/A

- **Can the installation process be easily reversed for decommissioning of the windmills?**
  Yes, it can
- **Will decommissioning projects related to oil and gas be a growing part of your business for the next five years?**
  The decom business segment is expected to grow; however, the new build and modification activity is still expected to form the major part of our business the next years.
- **Are you planning to expand your international operations related to decommissioning projects or will your main focus be in the Norwegian sector for the next five years?**
  The decom business segment is expected to grow with engagements also outside the Norwegian sector.
- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**
  Yes and no. Yes, Offshore Wind will be part of our decommissioning. No, we have not been involved yet

Appendix F. Minutes of meeting AF Decom 24th of April 2019

This document is a summary of minutes of meeting at AF Decom on the 24th of April 2019.

Person 1, AF Decom
Person 2, AF Decom
Jens Christian Lindaas, HVL
Børre Mæland, HVL
Martin Urnes, HVL

Questions related to company visits.

Introduction

- **Which decommissioning projects (oil and gas) have your company been involved in?**
  AF Decom has been involved in many projects concerning removal, dismantling and recycling; Ekofisk-tank, Ekofisk Cession 1 and 2, Murchison, Janice, B11 and H7, Inde Field.
- **What has been your Scope of Work in these projects?**
  Typical Scope of Work for these projects and AF Decom in general is the removal and/or dismantling/recycling. AF Decom has both been main contractor, but also sub-contractor with Heerema.

Cutting offshore

- **What methods and tools have been used for cutting/dismantling the structures (subsea and topside)?**
  Heerema and subcontractors have mainly been responsible for this part.
- **What is your experience using these methods/tools?**
  N/A

Logistics

- **How have the parts been lifted onboard the vessel(s) and transported to the onshore base?**
  Main principle is reverse-installation, where a heavy lift vessel lifts it onto deck and transport it to Vats. The deep quay facilities are the main advantage for AF Decom. Old platforms are built module based, and new ones are also built to be removed as a few big pieces/modules.
- **Which types of vessels have you been using?**
  Heavy lift vessels like Heerema´s Thialf and similar deepwater construction vessels. These can lift entire jackets and platform decks. Jack-up vessels have also been used, similar to Pacific Osprey.
- **Has towing of structure elements been used?**
  Yes, only for floating loading buoys. Other than that – no.

Cleaning

- **Do you consider cleaning the parts of the rig/structure before and during decommissioning?**
  Yes, cleaning is an important part of the decommissioning process. This relates both to removal of marine growth and removal of hydrocarbons and other deposits inside pipes. High pressure water jet is being used for this purpose.

Onshore dismantling /recycling /waste disposal

- **Which onshore bases or quay facilities have you been using for the further dismantling and recirculation process?**
  They have been using their own facilities at Vats in Rogaland, Norway. This is a facility specially designed for this purpose with large quay areas, deepwater quays that can accommodate heavy lift vessels, and purpose made cleaning/filtering system to handle water spills and chemicals.

- **Which cutting methods and tools have they been using?**
  Oxy-propane due to its fast nature of cutting and low cost. Shear cutter hanging from a crane, but also shear cutter mounted on excavators.
  AF Decom has a stationary shear cutter for 2500 tones – the worlds biggest!
  They were looking into the possibilities of wire-cutting onshore. Automation is something they want to get into. They will additionally look into the use of explosives in one of the future dismantling projects.
- **Where has the material been sent for further processing/recirculation?**
  Stena Recycling, Eco-fiber, HIM, SIM, Celsa (for pure steel). They have an extensive NORM-check on everything leaving the site. (NORM –naturally occurring radioactive material.)

Wind farms

- **Have you been involved in installation of offshore windmills? Which windmills/parks?**
  Not involved in wind turbines so far.
- **What has been your Scope of Work in these projects?**
  N/A
- **Can the installation process be easily reversed for decommissioning of the windmills?**
  Yes, but what is most cost effective is most likely a different method.

Business /marketing

- **Will decommissioning projects related to oil and gas be a growing part of your business for the next five years?**
  If they can earn money.
- **Are you planning to expand your international operations related to decommissioning projects or will your main focus be in the Norwegian sector for the next five years?**
  Reference is made to a later question.

- **Are you interested in entering the business regarding decommissioning of wind parks? Have you already been involved in such projects? If so, what has been the Scope of Work?**

  Yes, if this can be done as serial decommission of many wind turbines. For AF Decom it is about getting big volume into the facilities in a short amount of time.
- **What needs do you identify in terms of labor market and infrastructure today and if entering this new business?**

  No special needs compared to what they have already in relation to facilities and personnel.
- **How important is international cooperation in general and for you particularly?**
  International cooperation and customers are already very important for them so this will not be something new.

- **Do you consider this "DECOM Tools"-project to be relevant and helpful? What do you expect from the project?**
  Yes, it will be interesting to join the "Expert Committee" to follow the project.

Appendix G. Nut splitter

Single-Acting Hydraulic Nut Splitters

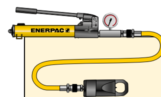
▼ Shown from left to right: **NC-3241, NC-1319, NC-1924**

NC, STN Series

Capacity:
49 - 882 kN (5-90 ton)

Bolt Range:
M6 - M48

Maximum Operating Pressure:
700 bar

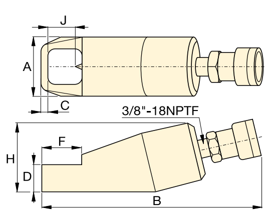


Tool-Pump Sets
Hydraulic Nut Splitters are available as sets (pump, tool, gauge, gauge adaptor, couplers and hose) for your ordering convenience.

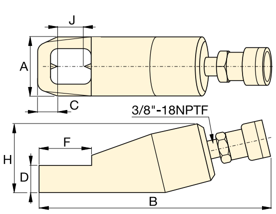
Nut Splitter Model Nr.	Hand Pump Model Nr.	Set Model Nr
NC-1924	P-392	**STN-1924H**
NC-2432	P-392	**STN-2432H**
NC-3241	P-392	**STN-3241H**

For Nut Splitter Model Nr.	Replacement Chisel Model Numbers	
	Moving	Static
NC-1319	**NCB-1319**	–
NC-1924	**NCB-1924**	–
NC-2432	**NCB-2432**	–
NC-3241	**NCB-3241**	–
NC-4150	**NCB-4150**	–
NC-5060	**NCB-5060**	–
NC-6075	**NCB-6075**	–
NC-1924D	**NCB-1924**	**NCB-1924D**
NC-2432D	**NCB-2432**	**NCB-2432D**
NC-3241D	**NCB-3241**	**NCB-3241D**

- **Compact and ergonomic design, easy to use**
- **Unique angled head design**
- **Two blade design (NC-D models) for time saving operation – nuts are split from two sides in one action**
- **Single-acting, spring return cylinder**
- **Heavy duty chisels can be reground**
- **Nut Splitters include spare chisel, spare set screw and wrench used to secure the chisel. A CR-400 coupler is standard.**



Single Blade Models (NC)



Double Blade Models (NC-D)

	Bolt Range (mm)	Hexagon Nut Range (mm)	Capacity ton (kN)	Oil Capacity (cm³)	Model Number	Dimensions (mm) A	B	C	D	F	H	J	(kg)
	**M6 - M12**	10 - 19	**5** (49)	15	**NC-1319**	40	170	7	19	28	48	21	1,2
	M12 - M16	19 - 24	**10** (98)	20	**NC-1924 ***	54	191	10	26	40	62	25	2,0
	M16 - M22	24 - 32	**15** (147)	60	**NC-2432 ***	64	222	13	29	51	72	33	3,0
	M22 - M27	32 - 41	**20** (196)	80	**NC-3241 ***	75	244	17	36	66	88	43	4,4
	M27 - M33	41 - 50	**35** (343)	155	**NC-4150**	94	288	21	45	74	105	54	8,2
	M33 - M39	50 - 60	**50** (490)	240	**NC-5060**	106	318	23	54	90	128	60	11,8
	M39 - M48	60 - 75	**90** (882)	492	**NC-6075**	156	393	26	72	110	181	80	34,1
	**M12 - M16**	19 - 24	**10** (98)	20	**NC-1924D**	54	168	22	25	50	66	26	3,8
	M16 - M22	24 - 32	**15** (147)	60	**NC-2432D**	64	275	25	31	65	78	33	5,4
	M22 - M27	32 - 41	**20** (196)	80	**NC-3241D**	77	305	31	37	80	90	43	7,2

Ordering Notes: Maximum allowable hardness to split is HRc-44. Not to be used on square nuts or stainless steel.
* Available as Tool-Pump Set, see note on this page.

Single-Acting Hydraulic Nut Splitters

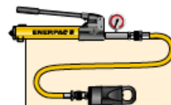
▼ Shown from left to right: **NC-3241, NC-1319, NC-1924**

NC, STN Series

Capacity:
49 - 882 kN (5-90 ton)

Bolt Range:
M6 - M48

Maximum Operating Pressure:
700 bar



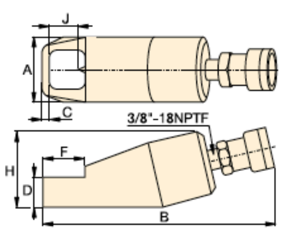
Tool-Pump Sets

Hydraulic Nut Splitters are available as sets (pump, tool, gauge, gauge adaptor, couplers and hose) for your ordering convenience.

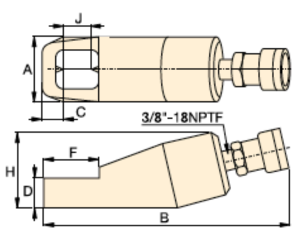
Nut Splitter Model Nr.	Hand Pump Model Nr.	Set Model Nr
NC-1924	P-392	**STN-1924H**
NC-2432	P-392	**STN-2432H**
NC-3241	P-392	**STN-3241H**

- **Compact and ergonomic design, easy to use**
- **Unique angled head design**
- **Two blade design (NC-D models) for time saving operation – nuts are split from two sides in one action**
- **Single-acting, spring return cylinder**
- **Heavy duty chisels can be reground**
- **Nut Splitters include spare chisel, spare set screw and wrench used to secure the chisel. A CR-400 coupler is standard.**

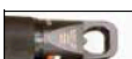
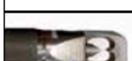
For Nut Splitter Model Nr.	Replacement Chisel Model Numbers	
	Moving	Static
NC-1319	**NCB-1319**	–
NC-1924	**NCB-1924**	–
NC-2432	**NCB-2432**	–
NC-3241	**NCB-3241**	–
NC-4150	**NCB-4150**	–
NC-5060	**NCB-5060**	–
NC-6075	**NCB-6075**	–
NC-1924D	**NCB-1924**	**NCB-1924D**
NC-2432D	**NCB-2432**	**NCB-2432D**
NC-3241D	**NCB-3241**	**NCB-3241D**



Single Blade Models (NC)



Double Blade Models (NC-D)

	Bolt Range (mm)	Hexagon Nut Range (mm)	Capacity ton (kN)	Oil Capacity (cm³)	Model Number	Dimensions (mm) A	B	C	D	F	H	J	(kg)
	**M6 - M12**	10 - 19	**5** (49)	15	**NC-1319**	40	170	7	19	28	48	21	1,2
	M12 - M16	19 - 24	**10** (98)	20	**NC-1924 ***	54	191	10	26	40	62	25	2,0
	M16 - M22	24 - 32	**15** (147)	60	**NC-2432 ***	64	222	13	29	51	72	33	3,0
	M22 - M27	32 - 41	**20** (196)	80	**NC-3241 ***	75	244	17	36	66	88	43	4,4
	M27 - M33	41 - 50	**35** (343)	155	**NC-4150**	94	288	21	45	74	105	54	8,2
	M33 - M39	50 - 60	**50** (490)	240	**NC-5060**	106	318	23	54	90	128	60	11,8
	M39 - M48	60 - 75	**90** (882)	492	**NC-6075**	156	393	26	72	110	181	80	34,1
	**M12 - M16**	19 - 24	**10** (98)	20	**NC-1924D**	54	168	22	25	50	66	26	3,8
	M16 - M22	24 - 32	**15** (147)	60	**NC-2432D**	64	275	25	31	65	78	33	5,4
	M22 - M27	32 - 41	**20** (196)	80	**NC-3241D**	77	305	31	37	80	90	43	7,2

Ordering Notes: Maximum allowable hardness to split is HRc-44. Not to be used on square nuts or stainless steel.
* Available as Tool-Pump Set, see note on this page.

T

Hydraulic Nut Splitters

Nut Splitter Sets

To provide maximum flexibility, NS-Series Nut Splitters can also be ordered in sets (NS-xxxSy). Select Nut Splitter size and pump style from the chart below.
To order additional Cutting Heads (NSH-xxxxxx), Cylinders (NSC-xxx) or Replacement Blades (NSB-xxx), see Selection Chart below.

SET SELECTION:

1. Select your Nut Splitter
2. Select your pump type

NS Series

Capacity:
917 - 1711 kN

Hexagon Nut Size:
70 - 130 mm

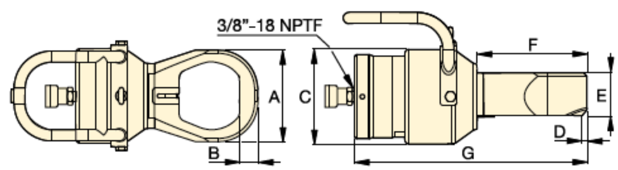
Bolt Range:
M45 - M90

Maximum Operating Pressure:
700 bar

▼ TOOL-PUMP SET SELECTION CHART

Nut Splitter Model Nr.	Tool-Pump Set Model Nr.	Pump Selection				Accessories Included			
		Hand Pump Model Nr.	Air Pump Model Nr.	Cordless Pump (230V) Model Nr.	Electric Pump (230V) Model Nr.	Pressure Gauge Model Nr.	Gauge Adaptor Model Nr.	Hydraulic Hose Model Nr.	Storage Case Model Nr.
NS-70105	**NS-70105SH**	P-392	–	–	–	GP-10S	GA-2	HC-7206	CM-4
	NS-70105SA	–	XA-11G 2)	–	–	2)	–	HC-7206	CM-4
	NS-70105SCE 1)	–	–	XC-1202ME	–	GA45GC 3)		HC-7206	CM-4
	NS-70105SEE 1)	–	–	–	PUD-1100E	GP-10S	GA-2	HC-7206	CM-7
NS-110130	**NS-110130SH**	P-802	–	–	–	GP-10S	GA-2	HC-7206	CM-4
	NS-110130SA	–	XA-11G 2)	–	–	2)	–	HC-7206	CM-4
	NS-110130SCE 1)	–	–	XC-1202ME	–	GA45GC 3)		HC-7206	CM-4
	NS-110130SEE 1)	–	–	–	PUD-1100E	GP-10S	GA-2	HC-7206	CM-7

1) For set with 115 Volt pump application replace last suffix "E"with "B" in model number.
Example : **NS-70105SCB** (set with XC-cordless pump, 115V);
Example: **NS-110130SEB** (set with PU-Series electric pump, 115 V)
2) XA-11G air pump features an integrated pressure gauge.
3) See page 134 for GA45GC details.



▼ NUT SPLITTER SPECIFICATIONS

Bolt Range (mm)	Hexagon Nut Range 1) (mm)	Capacity ton (kN)	Oil Capacity (cm³)	Model Number 2)	Dimensions (mm) A	B	C	D	E	F	G	(kg)	Cylinder 3)	Cutting Head 3)	Replacement Blade
M45 - M52	70 - 80	**103** (917)	377	**NS-7080**	132	28	180	8,0	81	186	412	37,0	NSC-70	NSH-7080	NSB-70
M45 - M56	70 - 85	**103** (917)	377	**NS-7085**	145	30	180	8,0	81	196	422	37,0	NSC-70	NSH-7085	NSB-70
M45 - M64	70 - 95	**103** (917)	377	**NS-7095**	160	32	180	8,0	81	201	432	38,5	NSC-70	NSH-7095	NSB-70
M45 - M72	70 - 105	**103** (917)	377	**NS-70105**	174	35	180	9,0	81	209	443	39,5	NSC-70	NSH-70105	NSB-70
M76 - M80	110 - 115	**193** (1711)	819	**NS-110115**	189	36	234	3,7	111	234	472	69,0	NSC-110	NSH-110115	NSB-110
M76 - M90	110 - 130	**193** (1711)	819	**NS-110130**	219	41	234	2,5	111	242	493	71,5	NSC-110	NSH-110130	NSB-110

1) Maximum allowable hardness to split is HRc-44. See page 275 for hexagon bolt and nut sizes and related thread diameters.
2) NS-Series Nut Splitters ship in two cases: One containing the NSC-Cylinder and one containing the NSH-Cutting Head. Assembly required.
3) Both, the NSH-head and the NSC-cylinder include a cutting blade.

Appendix H. Diamond wire saw

MIRAGE
PORTABLE PERFORMANCE

MDWS
Diamond Wire Saw

Rev 1.2

Description

The Mirage Diamond Wire Saw range of four machines (MDWS) are designed for underwater cutting of items such as multistring casings, piles, platform legs and wellheads.

Applications

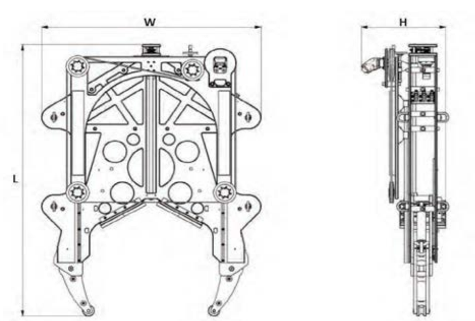
The MDWS uses abrasive cutting technology that is extremely effective in different subsea environments and is ideal for quick cutting through dissimilar materials and resisting compressive forces.

The wire cutter allows circular cutting on all sides, preventing the wire from getting pinched on materials that would otherwise damage lathe and mill type tooling. Customized saws are available by special order.

While the machine can be used topside, it is not considered a cold cutting method when used for surface operations.

Key Features

- Hydraulic Clamp & Auto Feed
- Models available to cut 6” - 84” OD Pipe
- Powerful Hydraulic Drive Wheel
- ROV and Diver Compatible
- Strong Aluminium Frame



	MDWS620	MDWS1638	MDWS3660	MDWS6084
Cutting capacity	6-20”(152-508mm)	16-38” (406-965mm)	36-60”(914-1524mm)	60-84” (1422-2032mm)
Feed stroke	26” (660mm)	44” (1117mm)	66” (1676mm)	90” (2286mm)
Length	85" (2159mm)	102" (2590mm)	143" (3632mm)	180" (4572mm)
Width	60" (1524mm)	75" (1905mm)	105" (2667mm)	142" (3606mm)
Height	30” (762mm)	30” (762mm)	30” (762mm)	30” (762mm)
Weight in air	912Lbs (413kg	1,250Lbs (566kg)	1,885Lbs (855kg)	2,285Lbs (1036kg)
Weight in salt water	520Lbs (235kg)	595Lbs (269kg)	1,243Lbs (536kg)	1,645Lbs (746kg)

MIRAGE PORTABLE PERFORMANCE

MDWS
Diamond Wire Saw

Shipping Information

		MDWS620	MDWS1638	MDWS3660	MDWS6084
Shipping weight	**Box 1**	1,431 Lb (649kg)	1,550 Lb (784kg)	1,896 Lb (860 kg)	2,585 Lb (1172 kg)
	Box 2			2.161Lb (980 kg)	
Shipping dimensions L x W x H	**Box 1**	97 x 71 x 42" (243x 178 x 106cm)	97 x 90 x 42" (247 x 228 x 107cm)	160 x 78 x 48" (407 x 197 x 121cm)	180 x 142 x 30" (457 x 361 x 76cm)
	Box 2	-	-	160 x 78 x 48" (407 x 197 x 121cm)	Details on request

Included as standard with this machine

The machine is supplied complete with packing list and manual.

- ✓ Storage / shipping box
- ✓ Packing list and manual.

Optional items you may also need

(Details available on request)

- Hydraulic power unit
- Hydraulic control panel
- Six pass hydraulic hose reels
- ROV compatible hot stab system (available for purchase or hire)
- Deployment basket (made to order)
- Flotation
- Consumables, such as diamond wire ropes

Set up and operation

The operator must be:

- Trained and conversant with the MDWS
- Able to identify the correct and incorrect use of static or portable machines.
- Comply with all local and internationally recognised safe use of powered machines.

Machine Availability

Purchase ✓ Rental ✓ Rental subject to availability

REGISTERED COMPANY ISO 9001: 2008

Contact Us

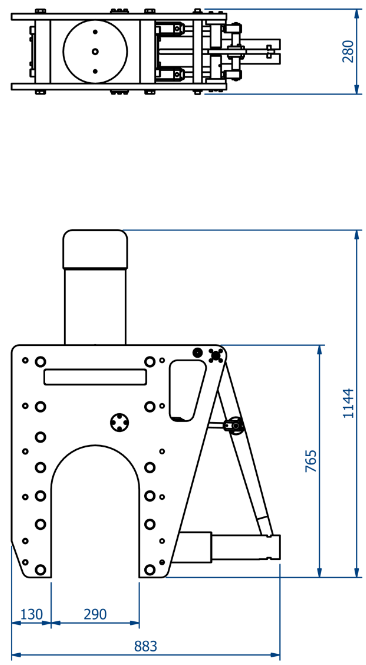
www.miragemachines.com

Actuant

Appendix I. Guillotine cutter

WEBTOOL™

HCV270 – Cable, Umbilical & Riser Cutter
Part No - 980216



- Heavy duty cable, umbilical and riser cutter for use in severe working conditions
- Hydraulically operated anvil for easy ROV deployment
- Robust plated steel construction
- All steel components are electroless nickel plated to resist corrosion
- Long blade life ensures that tool maintenance is kept to a minimum
- Optional intensifier panel is available
- Cutting capacity – Maximum Ø270mm
- Can be used at any water depth
- Suitable for cutting cables, hydraulic lines, riser and umbilicals
- 690 bar maximum input pressure for main cylinder
- 210 bar max input pressure for anvil
- Approx weight – 352kg
- Standard tool is shown above. Bespoke and custom designs to suit special applications are available on request

Appendix J. Support structures

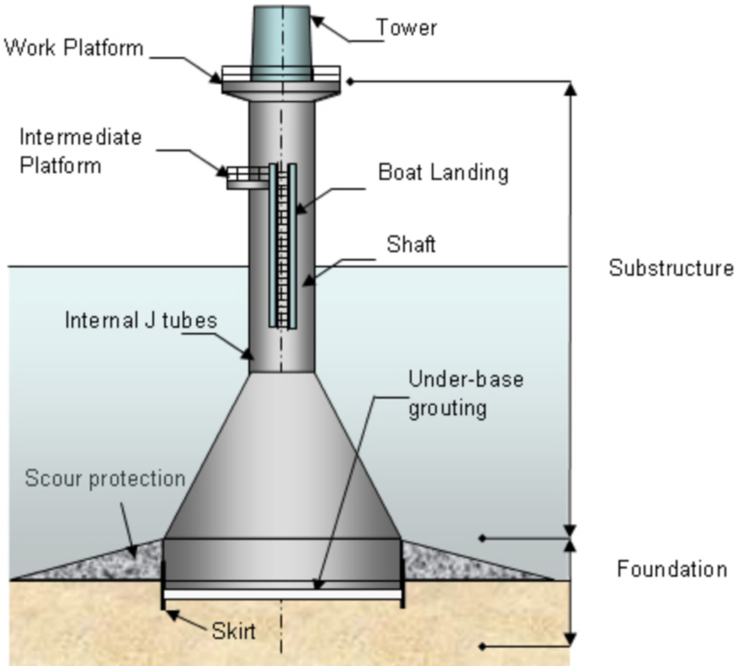


Fig 10 Gravity base [27]

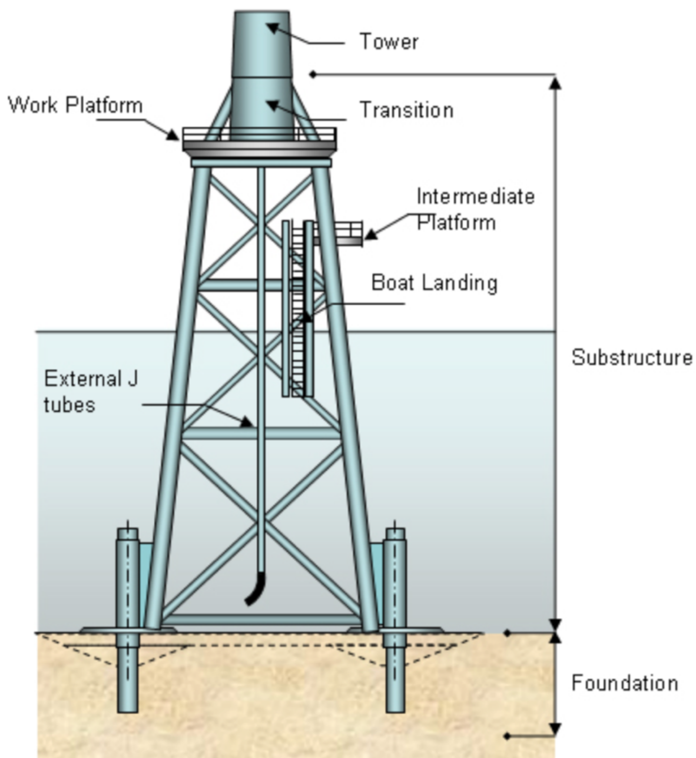


Fig 10 Jacked foundation [27]

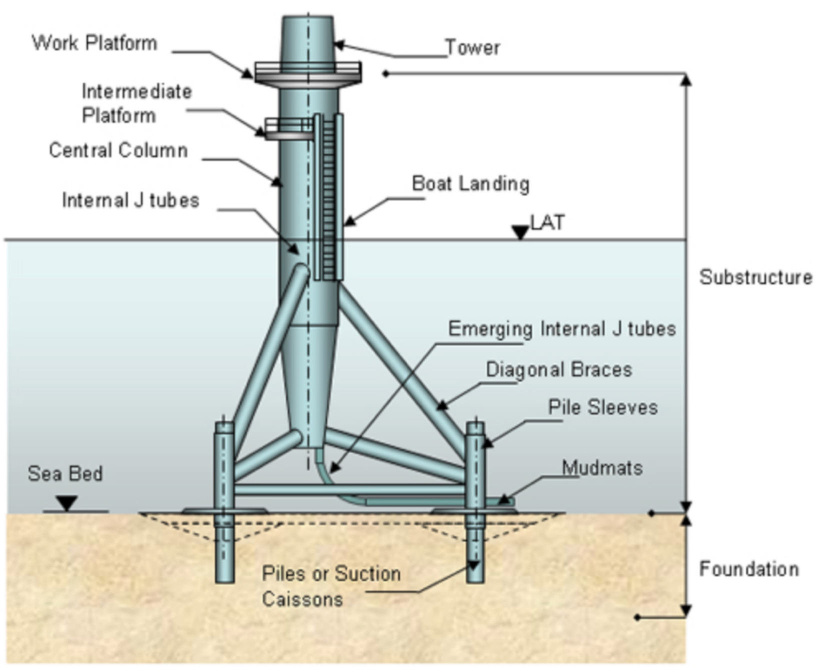


Fig 10. Tripod [27]

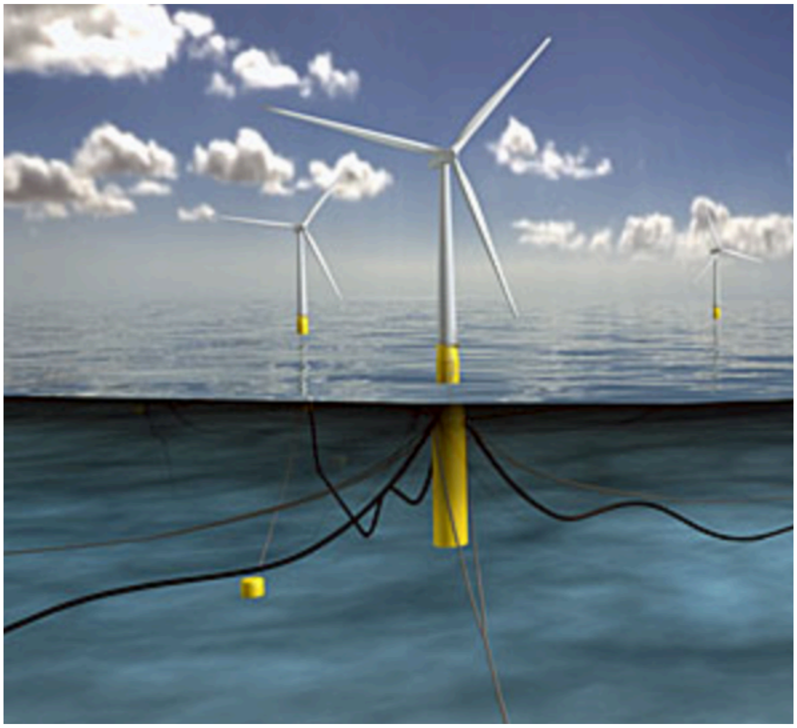


Fig 10. Hywind, floating turbines [28]