# Wind Farm Decommissioning

Celine Henriksen
Jørgen Osnes
Grete Eiane

Bachelor's thesis in Energy Technology
Bergen, Norway 2019

Høgskulen på Vestlandet

To assess the decommissioning process of an offshore wind farm considering cost, market, the effect on the environment and look at alternatives to decommissioning.

Celine Henriksen
Jørgen Osnes
Grete Eiane

Department of Mechanical- and Marine Engineering
Western Norway University of Applied Sciences
NO-5063 Bergen, Norway

Høgskulen på Vestlandet
Fakultet for Ingeniør- og Naturvitskap
Institutt for maskin- og marinfag
Inndalsveien 28
NO-5063 Bergen, Norge



| | |
|---|---|
| *Norsk tittel:* | Avvikling av vindmølleparker til havs. |
| Authors, student number: | Celine Henriksen, 182398<br>Grete Eiane, 182409<br>Jørgen Osnes, 148129 |
| Study program: | Energy Technology Engineering |
| Date: | May 25th, 2019 |
| Report number: | IMM 2019-05 (M82) |
| Supervisor at HVL: | Professor Richard J. Grant |
| Assigned by: | Equinor ASA |
| Contact person: | Dr. Wei He |

Number of files: 3

# Preface

This thesis is carried out to conclude a Bachelor of Science degree. It is written at the Department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (WNUAS). The study programme is Energy Technology. This thesis represents 20 credit points which represents 540 working hours. The topic was given by Dr Wei He, of Equinor ASA. The internal academic supervisor from WNUAS is Professor Richard J. Grant.

The purpose of this thesis is to assess the decommissioning process of an offshore wind farm considering cost, market, the effect on the environment and alternatives to decommissioning. It undertakes a very broad approach to an immature marked. This has been very challenging but at the same time very rewarding.

We highly appreciate the support from individuals and companies which have helped us during the course of this research project. We want to thank our internal supervisor Professor Richard J. Grant. We would also like to thank Dr. Wei He. Furthermore, we specifically would like to thank Johannes Thrane (AF Offshore Decom), Leif Winther (Ørsted A/S), Kim Madsen (Momentum Gruppen A/S), Andrés Olivares (HVL Haugseund), Lizet Ramirez (WindEurope), Andre Svanes (Norwegian Energy Partners) and Magnus Jansson (Vattenfall AB) for given us insight and sharing their knowledge and experience regarding the topic.

Bergen, May 2019

## Abstract

Decommissioning is the planned end-stage of offshore wind farms after their service life comes to an end. Up until 2019, only eight offshore wind farms have been decommissioned globally, meaning there is limited experience on the topic.

After the first offshore wind farm Vindeby, which was commissioned in 1991, 105 offshore wind farms have been installed, with a total power capacity of 18 430 MW. A market analysis has been conducted, and it predicts a growth in the sector. The planned installed capacity is predicted to reach 77 745 MW in 2030, with a yearly growth of newly installed capacity from 3 678 to 6 507 MW.

Eventually, all these wind farms will reach the end of their service life. Predictions made, based on available data, shows that from the year 2035 the capacity of farms that will be decommissioned will range from 3 000 to almost 7 000 MW yearly. There are many uncertainties regarding the cost for this work. Based on several calculations this is estimated to range from 255 000 GBP to 425 000 GBP per MW.

For the purpose of this thesis the decommissioning process of a wind farm is divided into four main components; the blades, tower, foundation, and cables. The sections will assess the process, environmental impact, and waste management for each component. The decommissioning process is regulated by the government. There are no standardised regulations for Europe, and the permits and regulations vary from each country.

However, decommissioning in offshore wind can draw on experience from the O&G sector. Techniques for offshore operations can be adapted for the decommissioning process, such as those used for cutting of piles and cables where internal abrasive water jet and diamond cutting methods are well practised; also, in the use of vessels.

Repowering is a suggested alternative to decommissioning. To this date the technology is too immature. Once the development in the turbine efficiency evens out repowering will become a more sustainable solution. On the other side, lifetime extension of the wind farm can be seen as more of a cost-effective solution compared to repowering.

It is recommended that a standardized certification of the turbines' lifetime should be in place to ensure the safety of extension.

## Sammendrag

Avviklingen av vindmølleparker til havs skjer på slutten av parkens levetid. Normalt vil årsaken være at komponentene har nådd slutten av sitt kommersielle liv. Per dags dato er det bare åtte vindmølleparker til havs som har blitt avviklet, noe som tilsier at det finnes lite erfaring på dette området.

Den første vindmølleparken til havs, Vindeby ble installert i 1991. Siden den gang har 105 vindmølleparker til havs, med en samlet effekt 18 430 MW blitt installert. Det er utført en markedsanalyse og resultatene viser en stor økning av installerte vindmølleparker i fremtiden. Den planlagte installerte effekten vil nå 77 745 MW i 2030 og det blir beregnet å være en årlig økning med mellom 3 678 til 6 507 MW hvert år.

Omsider vil alle disse vindmølleparkene nå slutten av sin levetid. Analysen er basert på tilgjengelig data, og viser at det fra år 2035 vil bli avviklet vindmølleparker på mellom 3 000 og nesten 7 000 MW årlig. Kostnadene knyttet til dette er usikre, men basert på flere egne kalkulasjoner er det estimert at kostnaden vil ligge mellom 255 000 og 425 000 britiske pund per MW.

I oppgaven er avviklingen av en vindmøllepark delt inn i fire hovedkomponenter; bladene, tårnet, fundamentet og kablene. Disse kapitelene vurderer prosessen, miljøpåvirkningen og avfallshåndteringen for hver av komponentene. Avviklingsprosessen er regulert av regjeringen. Det finnes ingen felles regler for Europa, og tillatelsene og reglene varierer derfor fra land til land.

Avvikling av havvind kan trekke erfaringer fra olje og gass-sektoren. Teknikker for offshore operasjoner kan tilpasses, for eksempel kutting av strukturer og kabler, samt bruk av fartøy. Internal abrasive water jet og diamond wire er blant kuttemetodene som kan brukes for å kutte fundamentet til vindmøllen.

Oppgradering av en vindmøllefarm kan også være et alternativ til avvikling. Derimot er dagens teknologi for umoden for markedet. Når markedet når et visst punkt med effektivisering av turbiner kan oppgradering bli en mer bærekraftig løsning. På den andres siden har forlengelse av levetiden av turbinene blitt en mer foretrukket løsning for å redusere LCOE. En standardisert sertifisering av turbinenes levetid vil sørge for sikkerheten ved en eventuell forlengelse.

# Content

## Abbreviations & Terminology

| | |
|---|---|
| *ARRAY CABLES* | *Cables that transfers electricity from the turbines to the substation.* |
| *BAR* | *A metric unit of pressure.* |
| *BOTTOM FIXES* | *Type of foundation that is fixed to the bottom of the sea.* |
| *CAPEX* | *Capital Expenditure. Expenses used on investment of fixed assets.* |
| *CFRP* | *Carbon-fibre-reinforced polymer.* |
| *DECEX* | *Decommission expenditures. Expenses used on the decommissioning.* |
| *DECOMMISSIONING* | *The process of disassembly and removal of the wind turbine.* |
| *DISCOUNT RATE* | *An interest rate used to determine the value of the future cash flow in the present.* |
| *EEZ* | *Exclusive Economic Zone is a sea zone prescribed by UNCLOS.* |
| *EXPORT CABLES* | *Cables that transfer electricity from the substation to shore.* |
| *FRP* | *Fibre-reinforced plastics.* |
| *GFPR* | *Glass-fibre-reinforced plastics.* |
| *GRID* | *A network for transferring electricity from producers to consumers.* |
| *HUB* | *A component of a wind turbine that connects the blades to the main shaft* |
| *IMO* | *The International Maritime Organisation.* |
| *J-TUBES* | *Steel tubes shaped in a J. They are used to guide the export power cables from the turbine to the seabed.* |
| *KINETIC ENERGY* | *Energy of motion.* |
| *KM* | *Kilometre.* |
| *kW* | *Kilowatt - equals 1 000 Watt.* |
| *LCC* | *Life Cycle Cost. The cost associated with a wind turbine or a wind farm through the whole life of the project.* |
| *LCOE* | *Levelized Cost of Energy. The average cost that a wind farm can produce electricity given in US/kWh.* |
| *MECHANICAL POWER* | *The rate at which work is done.* |
| *MONOPILES* | *A type of bottom fixed foundation.* |
| *MW* | *Megawatt equals 1 000 kW.* |
| *NACELLE* | *Cover housing that houses all the generating components in a wind turbine.* |
| *OFFSHORE* | *Sea-based activities.* |

| | |
|---|---|
| *ONSHORE* | *Land-based activities.* |
| *OPEX* | *Operating expenditures. Expenses coming from operating the wind farm.* |
| *OSPAR* | *Convention for the protection of the Marine Environment of the Northern-East Atlantic.* |
| *O&G* | *Oil and gas.* |
| *REPOWERING* | *Upgrading a wind farm to extend its lifetime and increase the efficiency.* |
| *ROV* | *An underwater Remotely Operated Vehicle.* |
| *SCOUR PROTECTION* | *Scour is caused by swiftly moving water that might scoop out scour holes. This can compromise the integrity of the structure. The protection will prevent this from happening.* |
| *SITU* | *The original place of placement.* |
| *SUBSTATION* | *A station that connects all the wind turbines and converts the electricity before transferring it to shore.* |
| *S355 & S500* | *Steel structure types. 355 and 500 dictates the strength of the steel.* |
| *UHP* | *Ultra High Pressure.* |
| *UNCLOS* | *The United Nations Convention on the Law of the Sea.* |
| *UNDERWATER CABLES* | *Can be both Array-cables and Export cables.* |
| *W* | *Watt – a unit of power defined as a derived unit of 1 joule per second.* |

# 1 Introduction

Wind power is one of the fastest growing energy sources in the world. As the worldwide demand for sustainable energy increases, it is expected that the offshore wind market will be a significant contributor to clean energy production. Figure 2 shows the total installation of wind energy in Europe for the last ten years. Since 2008 there has been a huge growth in offshore wind. Germany and the United Kingdom are among the biggest contributors to this total wind installation in Europe [1].

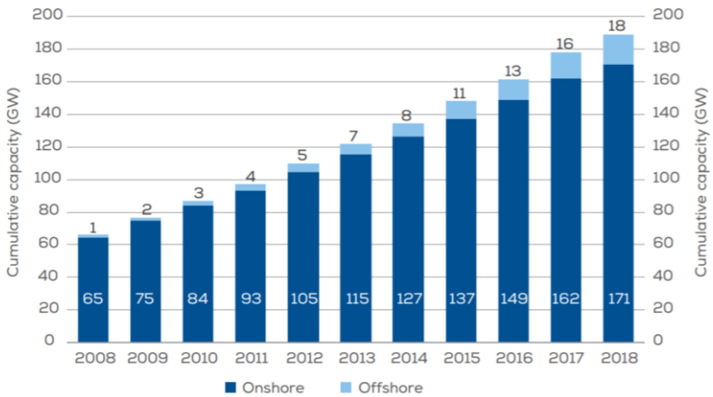


*Figure 2 - Total Installation of Wind Energy in Europe [1]*

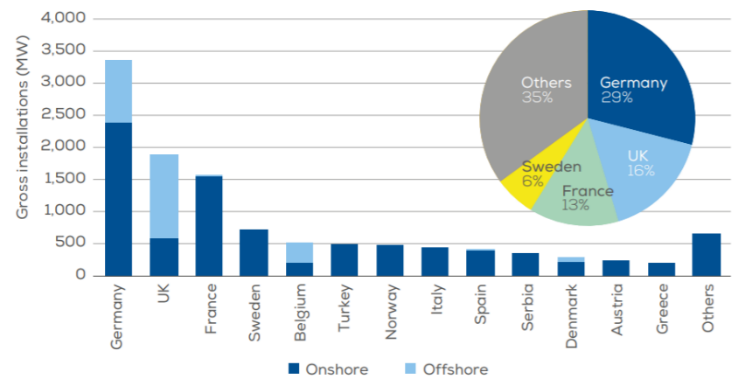


*Figure 1 - Installed Wind Power Capacity in Europe [1]*

Offshore wind power demands higher investments cost compared to onshore wind, but there are several advantages for placing the turbines offshore [3]. Prices will come down due to innovations and new technology, making it an even more attractive market. While the size of the turbines increases, so does the energy output, meaning that they are becoming more cost-efficient [2].

Since Vindeby, the first offshore wind farm which was installed in 1991 off the coast of Denmark, 105 offshore wind farms have been commissioned. These farms consist of 4 543 turbines, adding in total 18 430 MW of installed capacity. In 2017, after Vindeby had been in service for 26 it had to be decommissioned. Eventually, all commissioned farms will reach the end of their service life. Since at this point in time, only a few farms have reached the end of their service, there is not enough experience yet on the topic of decommissioning.

Decommissioned projects have been small relative to today's installations, in terms of both numbers and sizes of turbines. So far, the reasons for decommissioning have been varied. Several turbines have been research projects, not intended for extended commercial operation. Decommissioned commercial offshore wind farms have consisted of turbines reaching no more than 2 MW, which is far from the average turbine size today at 6,8 MW [1].

In years to come, the volume of decommissioning projects will increase as more commercial offshore wind farms reach the end of their operating lifetime. Operators are comparing options for lifetime extension or possibly re-powering using new turbines on the existing foundations rather than fully decommissioning the farm. With the option of fully decommissioning it is essential to find a cost-effective method while considering factors such as environment and safety. By now, there is limited experience on the topic. For the future, it must be determined solutions for decommissioning of offshore wind farm. There are a lot of uncertainties regarding both cost and the environmental impact on removing the turbines components from the seabed.

A number of cost estimates have been performed to date; with previous estimates, according to DNV GL, costs have been underestimated [4]. That is why it is important for the industry to figure out all the principal and significant uncertainties involving in the decommissioning process, making sure that it will be done in a sustainable and cost-efficient way.

The main components of an offshore wind turbine are heavy, and the material needs to be handled in a proper way after its lifetime to reduce the environmental impact significantly. Waste should either be recycled, reused, or incinerated with the energy recovery. Some of the components may have a longer lifetime, meaning that repowering can be an option above decommissioning.

## 1.1 Aim and Objectives

The aim for this thesis is:

To assess the decommissioning process of an offshore wind farm considering cost, market, the effect on the environment and look at alternatives to decommissioning.

In order to achieve the aim, several objectives have been made, which are:

- Analyse the market for decommissioning of offshore wind farms.
- Study already decommissioned and repowered projects of offshore wind farms.
- Recycling of turbine parts and waste management.
- Look at what will happen if the farm is fully decommissioned. Is it better for marine life to leave some structures as it is?
- Calculate an estimated total cost of decommissioning and compare these numbers to installation and lifetime cost.
- Calculate the estimated decommissioning cost for the main components.
- Look at experiences from the oil and gas sector.
- Look at alternatives to decommissioning; repowering and lifetime extension.

## 1.2 Assumptions

- All offshore wind turbines that are being referred to, if not stated otherwise, are bottom-fixed with a monopile foundation.
- The lifetime of a wind turbine is set to 20 years, based on DNV GL´ Standard, as described in 1.4.1 Lifetime.
- The cost calculation includes only the turbine. Meaning all other expenditures are calculated as a part of the turbine.
- All prices are given in GBP if other is not specified. Any conversions are based on the conversion rate at 05.05.19.
    - EURO to GBP = 0,85
    - USD to GBP = 0,75

## 1.3 Limitations

- There will be difficulties in getting data on the cost and assumptions are based on the reports used.
- The thesis will only focus on the principal components of the whole turbine and neglect all the internal component.
- The permits being discussed in the thesis under decommissioning and empowering will be based on The United Kingdom's regulations.
- All references in this thesis will refer to horizontal-axis wind turbines (HAWT).
- This thesis will not be focusing on energy production and lifetime energy (LTE).
- Decommissioning/repowering will only be in terms of whole wind farms and not for research projects or repairing single turbines.
- This thesis is limited to Europe and Europe´s offshore wind farms.

## 1.4 Reference Wind Farm

To be able to give some context to the thesis the mass and dimensions of three wind turbines are presented in Table 1. The turbines are having a power capacity of 5, 8, and a 10 MW.

For the purposes of this document, a 1 GW reference wind farm is also used. The farm consists of 100 Vestas 10,0 MW turbines located 60 km from shore in 30 meters water depth.

| Turbine | 5 MW | 8 MW | 10 MW |
|---|---|---|---|
| Rotor Diameter | 126 m | 164 m | 178,3 m |
| Tower height | 87,6 m | 106,3 m | 115,6 m |
| Hub height | 90 m | 110 m | 119 m |
| | | | |
| Blade mass | 17 740 kg | 35 000 kg | 41 716 kg |
| Tower mass | 347 460 kg | 558 000 kg | 605 000 kg |
| Hub mass | 56 780 kg | 90 000 kg | 105 520 kg |
| Nacelle mass | 240 000 kg | 285 000 kg | 446 036 kg |

*Table 1 - Reference Dimensions for Turbines [5]*

Both the reference farm and all other wind turbines in this thesis are referred to horizontal-axis wind turbines.

### 1.4.1 Lifetime

When designing wind turbines, a design lifetime of 20 years is generally assumed as a basis for dimensioning according to DNV GL Standard report. IRENA anticipates that larger turbines produced in the future may have an extended lifetime of up to 30 years. However, this thesis operates with a lifetime of 20 years for both the reference wind farm and all other turbines mentioned [6].

## 1.5 Methodology

The intention of this section is to describe the methodology used in this thesis. The methodology consists of literature studies, interviews, market analysis, and cost estimation.

Most of the information in the thesis were collected through a literature study of research articles, previous studies, and reports. Since the market of decommissioning is immature and there is not a lot of experience to rely on, it was important to find cases where decommissioning and repowering had been done before.

All sources employed in this thesis has been carefully considered against the principle of independence. Partial sources are reviewed against each other and discussed to create a neutral and factual report. During the assignment, the emphasis has been placed on a long-term perspective making the solution as sustainable as possible.

***Interviews***

To gather more information regarding decommissioning, interviews were conducted. Several companies in the industry were contacted. However, few of them were willing to reveal information at all due to confidentiality. Decommissioning is a part of the offshore wind market where experience is still lacking; although the commercial competition is high. That is why many of the companies are being secretive about the costs, impact, and methodology.

Fortunately, we got in touch with the one responsible for the decommissioning of Vindeby, Leif Winther and Magnus Jansson who was project manager of the decommissioning of Utgrunden. In addition, Kim Madsen from Momentum Gruppen A/S shared their experience with the repowering of the offshore wind farm Bockstigen.

Interviews were conducted and the questions were adapted to either the decommissioning or repowering process. Getting information from companies who have been involved with the decommissioning/repowering processes offshore has been valuable for the thesis and it has given a better insight.

***Oil and Gas Sector***

The oil and gas (O&G) sector are important for the decommissioning process as a lot of experience on offshore operations can be adapted in the offshore wind sector. To gather information, interviews have been made concerning relevant cutting projects considering piles where the technology used could be scaled for similar purposes in offshore wind structures. The Sales Manager, Mark Weeks, from RGL Services was contacted. RGL Services is the largest provider in the United Kingdom of abrasive water jet cutting. In addition, Johannes Thrane, the Vice President in AF Offshore Decom. AF Offshore Decom are experienced in decommissioning of O&G platforms in the Northern Sea and was able to provide useful information for this thesis.

***Conferences and workshops***

Another way to approach the industry was to attend several conferences and talks about offshore wind. We attended the workshop DECOM Tools in Haugesund. DECOM Tools is a funded project by EUs Interreg North Sea to develop eco-innovative end-of-life concepts for offshore wind farms. Their aim is to reduce decommissioning cost by 20%, and the environmental footprint by 25%.
There were several companies from the industry present for discussions of the main issues with decommissioning and how to solve them in the future. Gaining experience and knowledge from the industry this way made it easier to connect the theory to the practical aspect of it.

Several other conferences about offshore wind farms were also attended, but the experience was that most companies did not have a plan for or wanted to share anything about the decommissioning process.

***Market Analysis***

A market analysis has been conducted to be able to understand today's market and to predict future decommissioning projects. To be able to say anything about the decommissioning projects we have been analysing existing and planned projects, together with ambitions for offshore wind power. After we had analysed existing and future projects, we used our assumptions of a wind farm lifetime of 20 years. With this assumption, we can estimate the size off future decommissioning projects, and when they will come. This will, among other things be very useful for the offshore support vessel market.

The calculations are mainly based on data from WindEurope and is only shared with us for academic use. All calculations are made using Microsoft Excel.

***Cost Estimation***

Due to a shortage of data and information about the economical aspect of offshore wind farms, calculations have been done based on available public data, to be able to assess the decommissioning cost. The calculations are mainly based on numbers from DNV GLs paper Logistics and Cost Reduction of Decommissioning Offshore Wind Farms, and BVGs Associates Guide (from now on BVG) to an Offshore Wind Farm. BVGs paper is written together with The Crown Estate and Catapult Offshore Renewable Energy. Calculations are done on the different aspects of the decommissioning process and then used as a guide for future cost. The information is presented in Microsoft Excel.

# 2 Offshore Wind Energy

Wind power is one of the fastest growing energy sources in the world. The technology has been mature since the 1980s, enabling rapid growth of the sector [7]. Since this time the cost of the wind turbines have fallen significantly and the capacity increased. Today, wind turbines are one of the most cost-effective ways to generate electricity [8].

## 2.1 Offshore Wind Farm Design

Both onshore and offshore wind turbines operate on a basic principle. The generator converts mechanical power to electricity from rotating rotor blades [9]. However, the support structures and foundations are more complex for offshore wind. The technology involves great challenges, not least by way of the requirements to withstand the marine environment.

## 2.2 Turbines

Figure 3 shows the main components of an offshore wind turbine system. It consists of a typical monopile foundation, the substructure, transition piece, tower, nacelle and rotor blades. The substructure connects the transition piece or tower to the foundation at seabed level.

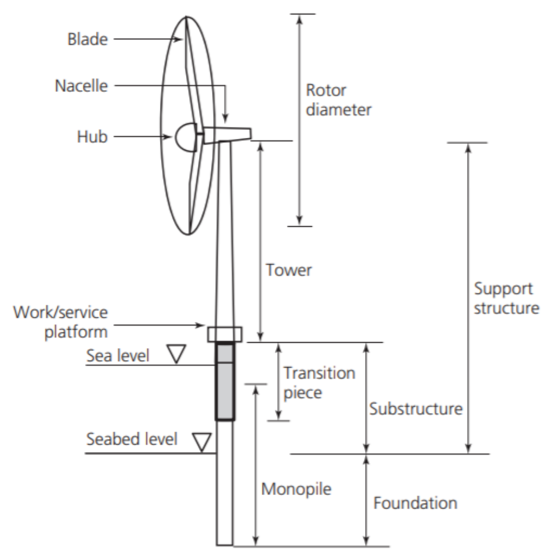


*Figure 3 - Various Components of a Wind Turbine [10]*

## 2.3 Different Types of Foundation

Offshore wind turbines use different types of foundation, both floating and bottom-fixed. The bottom-fixed foundations have in common that they are rooted in the seabed and restricted to waters less than 50 meters deep, as seen in Figure 4 [7].

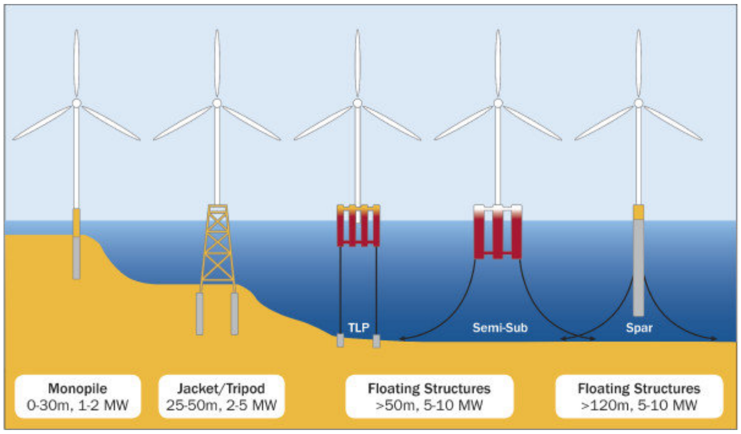


*Figure 4 - Different Types of Offshore Foundations [11]*

The monopile is currently the most common among the offshore foundations because of the easy installation process in shallow water depths. The structure is made of a cylindrical steel pile. The pile is driven 10 to 20 meters into the seabed depending on the type of underground conditions. This structure is well suited for water depths ranging from 0-30 meters [7].

The monopile was, in the beginning, predicted to be uncompetitive compared to other structures in water depths of more than 25 meters with a rated capacity of 5 MW or more. Monopile design is now largely improved. There has been huge innovation in design, manufacturing processes and installation tooling meaning monopiles are now expected to remain cost-competitive with larger turbines in sites of deep-water. This means that monopile will still be a significant part of the market in the future [12].

Figure 5 shows that monopiles makes up in total about 81% of all offshore foundations in 2018, which means that will be a huge market in monopile decommissioning [1].

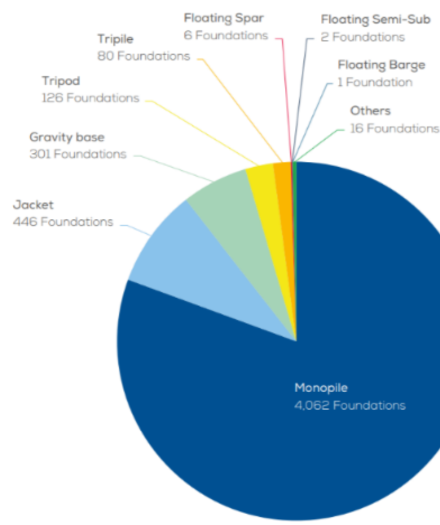


*Figure 5 - Numbers of Foundations of Offshore Wind Turbines [1]*

## 2.4 Offshore Wind Farm

Offshore wind farms are designed specifically for the marine environment. As illustrated in Figure 6 array cables link the various wind turbines to each other and to the offshore substation where the electricity is transformed. From the substation, the electricity is brought to shore by an export cable. The export cable connects the offshore substation to an onshore substation. The energy will join the onshore grid before it is transported through the distribution network [13].

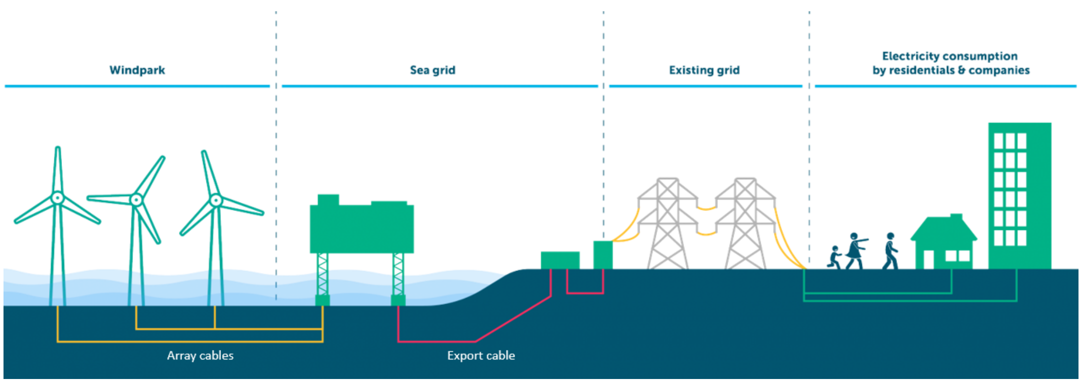


*Figure 6 - Grid Connected Offshore Wind Farm [13]*

The capital cost of energy from offshore wind farms are in general higher compared to onshore installations. This is caused by the extra costs of civil engineering for the substructure, higher electrical connection cost and the higher specification materials needed to resist the corrosive marine environment. On the other hand, there are many advantages to offshore wind farms. Offshore wind speeds are normally higher and more consistent than on land. When located offshore, the visual and acoustic impact is small, meaning huge areas can be used. Maritime transport is easier compared to on land. There are a few limitations regarding cargo and dimensions in comparison when transporting the turbine. This means that offshore wind turbines can reach larger unit capacities and sizes than onshore wind turbines [14].

## 2.5 Future Size of Turbine

The levelized cost of energy (LCOE) of a typical offshore wind farm commissioned in 2015 was about 127,5 GBP/MWh on average, compared to 280 GBP/MWh in 2001. The most significant technology innovations were the introduction of turbines with larger rotors and a range of innovations in foundations. Offshore wind turbines will continue further evolution. The increase in rated capacity will continue, reaching 20 MW in the future [12].

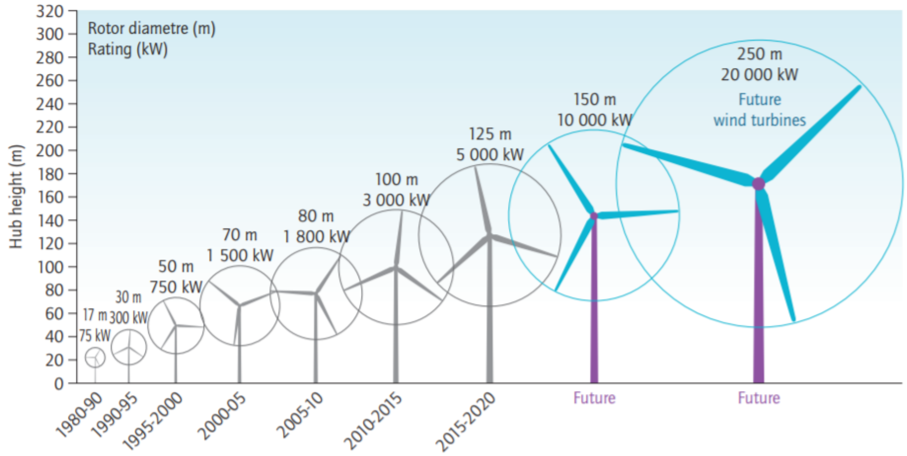


*Figure 7 - Future Size of Wind Turbines [12]*

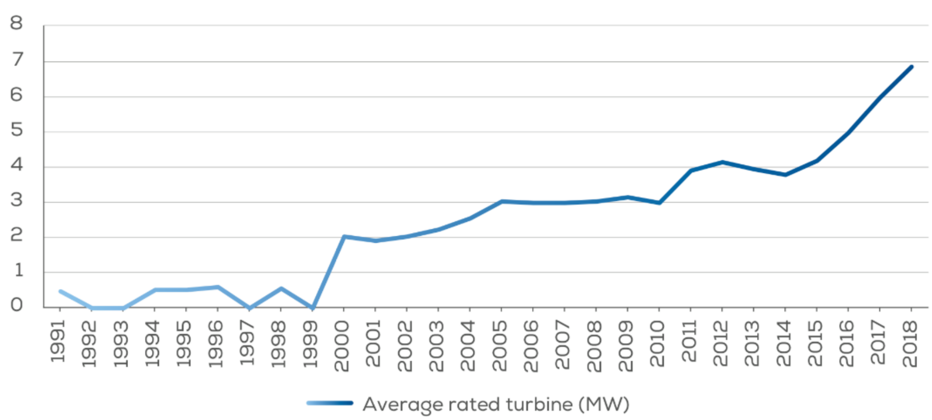


*Figure 8 - Average Yearly Increase Rated Turbine (MW) [1]*

**Error! Reference source not found.**Figure 8 illustrates the yearly increase in the average turbine size. Since 2014, there has been a yearly increase in the average turbine size of about 14%. In 2018, the average rated capacity of an offshore wind turbine was 6,8 MW, which is 15% larger than in 2017 [1].

The main driver to produce bigger turbines is the LCOE. Turbine innovations may result in higher capital expenditure (CAPEX) per MW, but improved reliability and energy production will reduce the levelized cost of energy in addition to operation and maintenance costs per MW [11]. In January 2019 Siemens Gamesa launched the 10 MW offshore wind turbine [16], while GE Renewable is testing their 12 MW wind turbine [17]. The largest turbine installed in 2018 was in the United Kingdom by Vestas was two 8,8 MW turbines with a rotor diameter of 164 m [18].

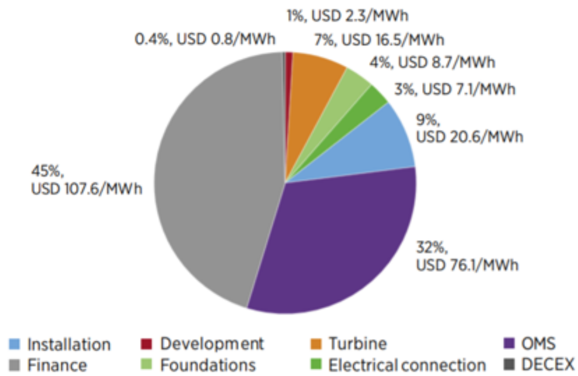


*Figure 10 - Contribution of Each Element to Cost of Energy for Typical Project Commissioned, end-2001 [12]*

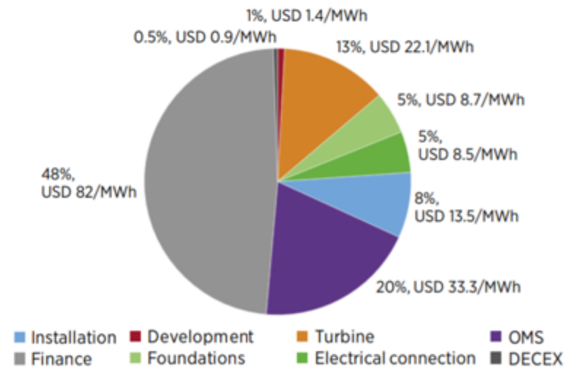


*Figure 9 – Contribution of Each Element to Cost of Energy for Typical Project Commissioned, end-2015 [12]*

Figure 9 and Figure 10 shows the cost breakdown for a typical project at the end of 2001 and the end of 2015. It is anticipated that the prices will come further down, and it will be mainly due to the use of larger turbines, with improved aerodynamic performance. Table 2 shows the predicted decrease in LCOE towards 2030 [12].

| CAPEX | OPEX | AEP | LCOE |
|---|---|---|---|
| -4,5% | -27% | 7,7% | -13% |

*Table 2 - Impact of Wind Turbine Technologies, 2016 – 2030 [12]*

## 2.6 Permits

In order to install an offshore wind farm, the operator must apply for permits. Permits are an allowance for the wind farm to be commissioned with certain conditions. The purpose of these conditions is to take care of and make sure that every aspect of the wind farm's lifetime is properly done according to the regulations. One of these aspects is decommissioning, which is an important part of the permits. These permits must be renewed to keep the farm running, otherwise, it must be decommissioned.

There are international regulations regarding the decommissioning process. The United Nations Convention on the Law of the Sea (UNCLOS*)* defines the nations' use of oceans in terms of guidelines regarding the environment, business and the management of the marine resources. The International

Maritime Organisation (IMO) is an organisation based on article 60 of UNCLOS, which regards the installations and structures in the exclusive economic zone (EEZ). IMO states that any coastal “state” must ensure that abandoned offshore installations must be decommissioned or removed entirely. This should all be done in such a way that it will cause no significant effect on the navigation or the marine environment. IMO also states further that in some cases it might be best to leave some structures as it is, if removing it will cause great damage to the environment, will be risky for the personnel involved or there are extreme costs involved. As for guidance of the funding of decommissioning there is none [19].

There are only a few countries who have provisions regarding the decommissioning process and how to fund it. Many countries apply these regulations from the O&G industry. In some countries, the planning of an offshore wind farm and the funding of the decommissioning may be requested, but in Germany and France this might not necessarily be the case at all, and some countries do not have provision. According to the report Offshore Wind Farm Decommissioning, proposing these requirements in the EU might be a good start for ensuring the maritime areas to be preserved. For now, there are only The United Kingdom, Denmark, and The Netherlands in the EU that has their own provisions for the decommissioning procedures and how to fund it [20].

***The United Kingdom***

The Energy Act from 2004 from the United Kingdom states that a decommissioning programme needs to be submitted, and the Secretary of State requires a person to be held responsible for this to be allowed a permit. This process is important for the government to make sure that the decommissioning will have financial security. The decommissioning will apply by the polluter pay principle and will also focus on the execution of it in a sustainable way [21]. The Crown Estate, who owns a big part of the sea bed, is the on granting the leases, under the guidelines of the Energy Act 2004 [19]. These permits are usually given out for a period of 40-50 years at each round [22].

With the Energy Act 2004, it is expected that the decommissioning handles an entire removal of the infrastructure. This minimizes the liabilities and the decommissioning programme should be based on this. But there are exceptions to this. Based on the case, the Energy Act 2004 opens to the possibility of only partially decommissioning due to environmental, cost and risk factors that are involved. To get this verification, usually, a third party needs to be involved, to confirm the increased risks of the environmental hazard a fully decommissioning might result in [21].

***Denmark***

The operator is legally liable for the installations for the offshore wind farm, and for making sure the site returns to its original state after decommissioning. There is an allowance of only partially removing if the removal causes an environmental hazard. The operator must provide a decommissioning plan for the government at least 2 years before the permit expires. And the financial guarantee must be provided to the Danish Energy Authority (DEA) for the decommissioning costs [20].

***Netherlands***

The permits require the developer to cut 4 meters below the seabed and this must be shown in the decommissioning plan. No consideration needs to be made for the cables. When the authorities approve of the decommissioning plan then the operator is liable for the execution. Since most of the developers are small companies, they are unable to provide a bank guarantee for 20 years. As a solution, the developers must make payments for a minimum of 10 years into a separate fund before the start of the construction. The government has access to this fund in case of insolvency [20].

As a note, the permits mention from here on will be based on the United Kingdom's regulations under the Act of Energy 2004.

# 3 Decommissioning

Decommissioning will occur at the end of a wind farm's lifetime. The reason for this may vary. The components of the wind farm may have reached the end of their commercial life. Another reason may be the costs that come with maintaining and refurbishing the farm might be too high to continue operating. Lastly, the permits given to operate the farm might have expired and has not been renewed [23].

Decommissioning is something that should be considered from the early on the planning stage of a wind farm. In this way, one might foresee unexpected costs that can occur. Before decommissioning every operator must have a decommissioning plan to obtain permits. Since every wind farm differ when it comes to size, distance from shore and weather conditions, there is no established methodology of decommissioning. However, the decommissioning should be divided into the three following stages [23]:

- Planning and understanding the site and coming up with the most efficient solution, both economical and sustainable.
- The removal process as illustrated in Figure 11.
- Monitoring the site recovery post-decommissioning and decide actions of waste management.

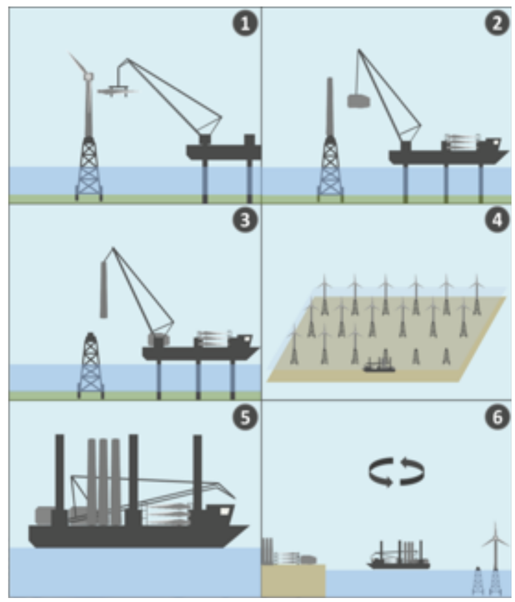


*Figure 11 - Steps of Decommissioning [24]*

## 3.1 Market

Decommissioning of offshore wind turbines is still an immature market in the energy sector. As shown in Table 3 it has only been done eight times in total. Half of these farms were only one or two turbines, and no farm was larger than 11 turbines. In the years to come the farms that are going to be decommissioned will be many times that size and the need for an efficient method of decommissioning will be essential to make offshore wind farms competitive against other energy sources. To be able to develop good solutions and an efficient supply chain it needs to be a marked for it.

With the assumption of a wind turbine's lifetime of 20 years, the market for decommissioning can be predicted based on what is already commissioned and what is planned in the future.

| Wind Farm | No. Of Turbines | Total Capacity (MW) | Foundation | Country | Year of Decommissioning |
|---|---|---|---|---|---|
| Utgrunden | 7 | 10,5 | Monopile | Sweden | 2018 |
| Vindeby | 11 | 5,0 | Gravity based | Danmark | 2017 |
| WindFLoat Phase 1 | 1 | 2,0 | Floating | Portugal | 2016 |
| Lely | 4 | 2,0 | Monopile | Netherland | 2016 |
| Hooksiel | 1 | 5,0 | Tripile | Germany | 2016 |
| Yttre Stengrund | 5 | 10,0 | Monopile | Sweden | 2015 |
| Robin Rigg | 2 | 6,0 | Monopile | The UK | 2015 |
| Nogersund | 1 | 0,2 | Tripod | Sweden | 2007 |

*Table 3 – All Decommissioned Offshore Projects by 2019*

## 3.1.1 Today

The total installed offshore wind capacity in Europe is growing rapidly. In 2018, 2 633 MW of offshore wind power capacity was installed. This was 17,5% lower than the record year 2017, but still one of the best three years so far. In 2018 both the United Kingdom and Germany decreased their annually newly installed capacity; however, Denmark opened the first new offshore wind farm since 2013 and Belgium doubled the total installation of 2017. Sweden´s wind farm Utgrunden was fully decommissioned. It consisted of seven turbines with a total of 10,5 MW installed capacity.

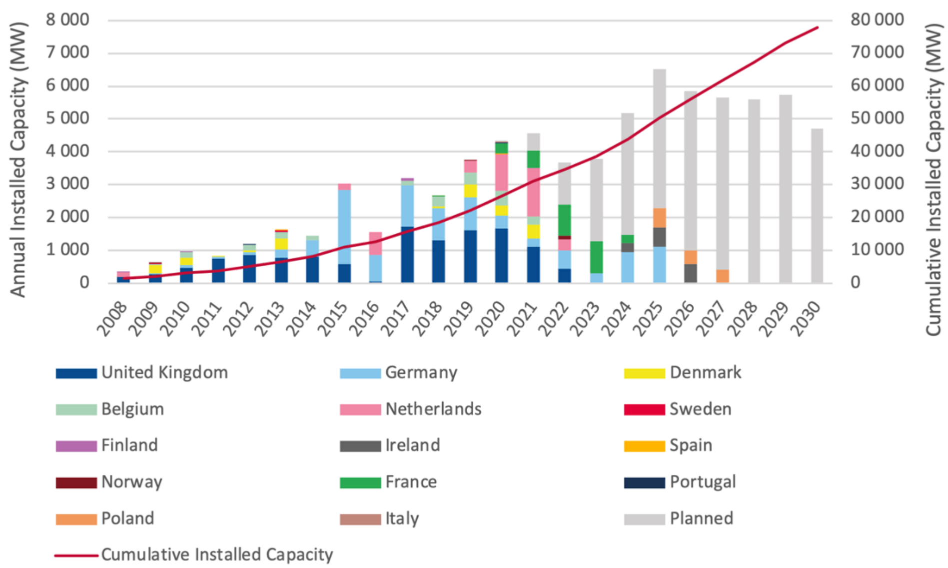


*Figure 12 - Annual Offshore Wind Installation and Predictions by Country and Cumulative Capacity (MW), 2008 – 2030*

With the commission and decommission of wind farms in 2018 Europe had a total of 18 430 MW installed offshore wind power capacity at the end of the year. The capacity is divided on 4 543 grid-connected turbines into 105 wind farms across 11 countries [1].

As shown in Figure 13 the United Kingdom represented 44% of Europe´s offshore wind power capacity at the end of 2018, Germany stood for 34%, Denmark 7%, and Belgium and the Netherlands 6% each. In total, these 5 countries represent 98% of all installed offshore wind power capacity in Europe. Other countries include Spain, Finland, France, Sweden, Ireland, and Norway, but these countries only represent 2% [1].

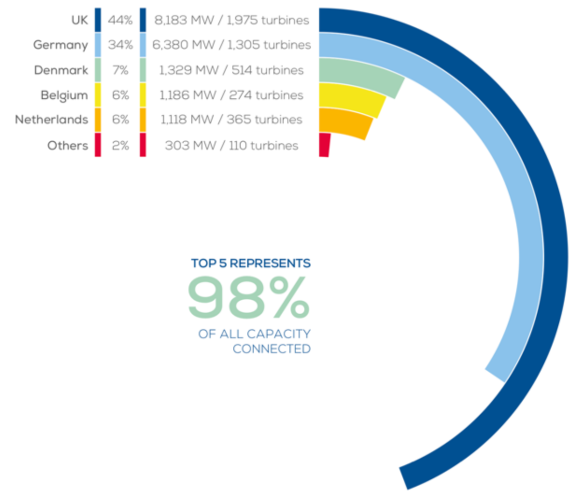


*Figure 13 - Cumulative Installed Capacity (MW) and Number of Turbines by Country [1]*

### 3.1.2 Predictions

In addition to the installed offshore wind capacity, some countries have high ambitions when it comes to installing new offshore wind capacity in the future.

Figure 12 shows that the installed capacity is planned to increase from 18 430 MW installed wind power capacity to 77 745 MW in 2030. The growth is predicted to be between 3 678 MW to 6 507 MW annually installed capacity every year.

### 3.1.3 Decommissioning Market

Predictions of the decommissioning projects from year 2028 to 2050 is shown in Figure 14. It shows that not only will most countries have decommissioning projects; but the size of wind farms, measured in MW, that will be needed to be decommissioned will increase many times over.

The annual size of decommissioning projects from 2028 to 2034 is estimated to be between 500 MW and 2 000 MW. These are some of the early offshore wind farms. From the year 2035 to 2044 the annual size of decommissioning is estimated to range from 3 000 MW to 5 000 MW. After this the projects will range from around 5 000 MW to around 7 000 MW each year.

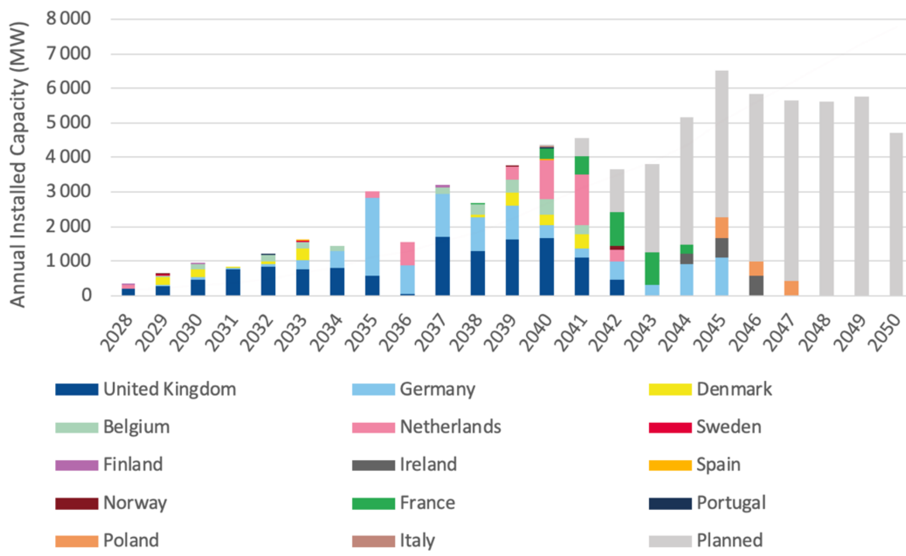


*Figure 14 - Predicted Annual Offshore Wind Decommissioning by Country (MW), 2028 - 2050*

For the next 20 years, most projects will happen in The United Kingdom and in Germany; but Denmark, Belgium, the Netherlands, Sweden, and Finland will also have some significant projects. It is also predicted that France, Poland, and Ireland will be some major players on the offshore wind market, and therefore, also have some significant decommissioning projects in 20-30 years.

## 3.2 Decommissioning by Components

This chapter focuses on the decommissioning of the main components of the offshore wind turbine. The turbine is divided into four components: Blades, tower, foundation, and cables. Each of the components will deal with aspects of the decommissioning process, environment, and waste management.

***Process***

The decommissioning process of the wind farm is usually the reverse of the installation; removing the electrical structure, the rotor, the nacelle, the tower, then the transition piece and finally removing the foundation [1].

***Environment***

How to decommission regarding what is best for the environment is both uncertain and challenging. To this date, there have only been few studies about the environmental impact offshore wind farm causes. However, a report from WWF showed that it was possible to install and operate an offshore wind farm without the environment being significantly damaged. The survey conducted by Environmental Impact Assessment studied Horns Rev, an offshore wind farm in Denmark, for some years which supported these statements. However, the survey is area limited, and cannot necessarily be linked to other wind farms, but it gives a good indication [25].

According to Crown Estate, the operators are obliged to undertake environmental surveys before planning a potential farm, this will give good information about potential existing wildlife and what the impact will be [26].

***Waste Management***

What the operators decide to do with the components after its lifetime also have a significant impact on the environment. The Energy Act 2004 states that the waste should either be recycled, reused, or incinerated with the energy recovery in line with the waste hierarchy. The last resort will be disposal at shore [21].

These regulations are based on the waste management hierarchy as shown in Figure 15. The most favoured option is the possibility of reducing waste by preventing it. This can be done by extending the components lifetime in the design process. The second alternative is the reuse of turbines in the second-hand market. The third option is recycling of the components and to use the material for either new turbines or new products. Then comes the recovery of the energy from the waste by incinerating. And finally, disposal of waste which is the least favourable option and should be the last resort in handling the waste [27].

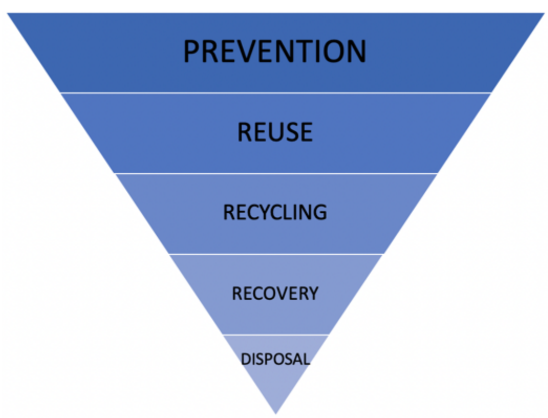


*Figure 15 - European Waste Framework Directive [27]*

Figure 16 displays the different components of the turbine. It shows the damaging effects they will have, and the level of uncertainty of handling a given component. The blades are the component that is most difficult to manage at the end of its lifetime, which will be mentioned in the next section [28].

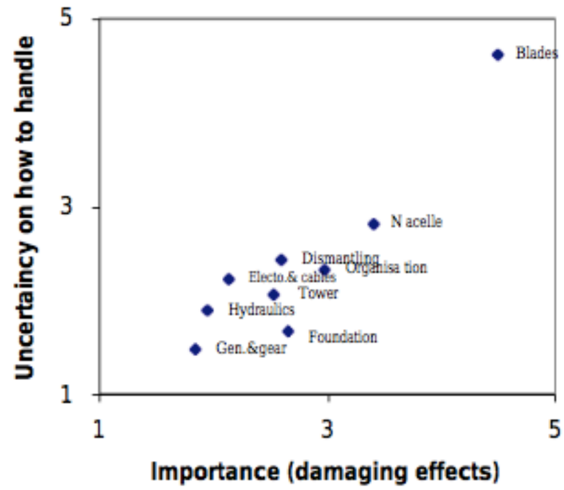


*Figure 16 - The Importance vs Uncertainty for Recycling of Each of the Components [28]*

## 3.2.1 Blades

### *3.2.1.1 Process*

The blades are usually the first things that are dismantled after the electrical infrastructure has been disconnected. There are several ways to decommission the blades according to the reverse process. This could be anything from dismantling all the blades separately along with the hub, rotor, and nacelle, or removing the whole turbine as one piece. The table below shows all the possibilities of the removal process [23].

| Removal concept | Description of lifts |
|---|---|
| Bunny ear and tower in 2 pieces | Single blade, nacelle, hub and two of the blades, tower in 2 pieces |
| Bunny ear and tower in 1 piece | Single blade, nacelle, hub and two of the blades, tower in 1 piece |
| Rotor and tower in 2 pieces | Hub and three blades, nacelle, tower in 2 pieces |
| Rotor and tower in 1 piece | Hub and three blades, nacelle, tower in 1 piece |
| Five pieces separately | All three blades individually, nacelle and hub, tower in 1 piece |
| Six pieces separately | All three blades individually, nacelle and hub, tower in 2 pieces |
| Removal in 1 piece | Blades, hub, nacelle and tower in one single lift |

*Table 4 - Different Ways of the Removal Process [29]*

### *3.2.1.2 Environment*

The environmental impact from the blades is significant when it comes to the bird population in the area. This includes everything from the displacement of existing habitats, risk of collisions and the wind farm becoming a mitigation barrier for the birds [25].

There are several measures to help to reduce these negative impacts. Some areas should avoid the development of offshore wind farms because of the displacement. Although some species have shown to adapt to the farms, there are still many vulnerable species that have shown to take significant harm from this. Developing a database for these vulnerable species might help with this problem. In addition, as the technology has developed this has resulted in farms being built in much deeper water and further from the shore. Naturally, this will help steer clear of these vulnerable habitats [25].

Studies have shown that collision with the bird and the turbines have not had any significant impact on the current populations, but the cumulative impact over time with the populations is more uncertain. Taking this into consideration and use the mitigations mentioned this might help against collision in the future. In addition, with proper spatial planning that takes into consideration, the importance of migration corridors might help to avoid these collisions. Adjusting the colour spectrum of the lights has also shown to reduce the attraction for birds to the wind farms [25].

#### *3.2.1.3 Waste management*

The turbine blades are the most challenging part when it comes to waste management of wind turbines due to its complex composition. The blades are only 2% to 3% of the mass of an entire wind turbine [30]. The blades are made from glass-fibre-reinforced plastics (GFRP) or carbon-fibre-reinforced polymer (CFRP). In consideration of today's and future projects, it is reasonable to say that the waste from both the production of blades and the decommissioning proses will increase in the years to come.

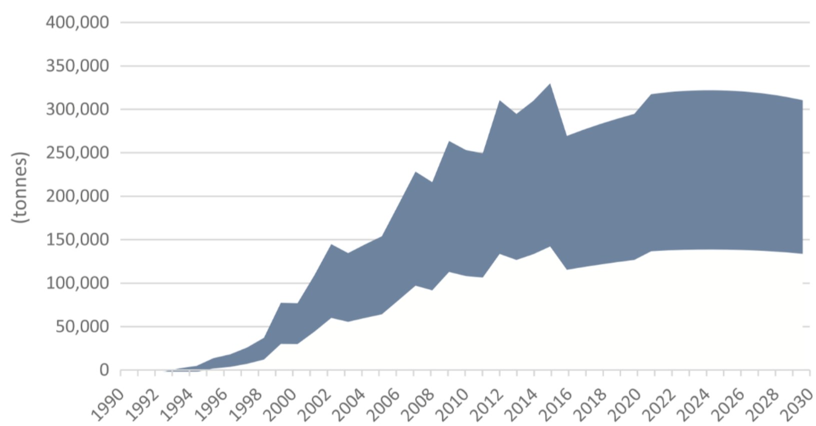


*Figure 17 - FRP Composites Used in Wind Turbines Blades [31]*

WindEurope predicts that the FRP composites in turbines will increase in the years to come [31]. With 20 years lifetime on a turbine, Figure 17 can be used as a prediction for future FRP composite disposal from wind turbines.

According to the waste hierarchy, the blades should be prevented from going to waste. It can be assumed that the lifetime can be extended through stronger materials and good service. This will extend the time before any waste management is needed. But how this will affect energy production is unclear, but it can be assumed that the design and material construction is optimized for cost-efficient energy production.

The blades can also be reused. Companies like Green Ener Tech [32], Repowering Solutions [33] and Spares in Motion [34] specialize in reselling turbines and components. This can be efficient as long as there is a market but may not cover the whole market when the really big wind farms will be decommissioned. Another way to reuse the blades is in architecture. There have been some cases where the blades have been used as street furniture [35] or as a playground [36].

*Figure 18 – Street Furniture, Rewind Willemsplein [35]*

*Figure 19 – Playground, Wikado [36]*

Research has also been undertaking on the use of wind turbine blades for artificial reefs. It is said to be less environmental impact than other methods, and good support for marine life reproduction. But the process of preparing the blades is complicated and there is still a lot of research that must be done before this is an actual alternative. There are also some uncertainties if the relatively low weight of the blades will make the reef unstable at the seabed [37].

Currently, there is no recovery process for carbon fibre-based products. Some companies, like Veolia, is currently working on multiple solutions to be able to recover the fibres [30]. A solution is to cut and crush the blades, then mix it up with other components. The result is a good solid fuel for the cement industry. The glass fibre mix can also be used within the cement matrix [30].

The last option is disposal and the blades would be landfill. With the predicted number of future decommissioned wind farm as shown in Figure 14, this could be a massive problem.

### 3.2.2 Tower

#### *3.2.2.1 Process*

The tower will be lifted from the foundation with the help of a vessel. The usually preferred way of dismantling is the opposite of the installation process, but all this depends on factors such as the site and size of the turbine. The use of different vessels will also depend on the removal of it. Whether it is a multifunctional vessel which does the lifting and the transportation to the shore, or there are separate vessels for each of these actions.

The transition piece is the part connecting the lowest part of the tower to the foundation. The piece weighs about 300 tonnes and includes platforms, J-tube cables, and access ladders. The cables which are connected to the tower and to the foundation will be disconnected and cut to make the lifting operation possible. The cutting of the transition piece starts when a crane is in position for the lifting operation. Another option for the removal is to lift the transition piece altogether with the foundation. However, this will weigh about 1 000 tonnes and will require specialized cranes and extreme safety measures [23].

In terms of decommissioning the substation, it can be divided into two parts: topside and its foundation. The topside will be transported to the shore as a single unit. The oil inside here must be either safely contained or emptied to reduce the risk of spilling. The same techniques that are used for the turbines will also be applied here. Two vessels, one for the topside and one for the foundation, will be necessary. When the topside is to be removed it must be disconnected from the grid and de-energized. Lifting points should be installed and the cutting of the welded stab-in connections between the substation and the foundation will take place. This means that the structures can be lifted separately; once they are lifted the transportation to processing them onshore will begin [23].

#### *3.2.2.2 Environment*

The noise that comes from construction during the decommissioning poses a threat to marine life. This might lead to forced movement out of foraging grounds, disorientation, hearing loss and tissue damage, and even death to marine life.

Operators should be aware of the habitat patterns in the area. In this way, it is easy to avoid reproductive periods when it comes to decommissioning and construction, so avoiding displacement of the marine life.

In addition, to avoid potential harm from intense sound pressure from pile activities the use of the *soft start* technique has been a standard procedure. The sound will increase over a 20-minute period, giving the marine life a chance to move away before full intensity is reached.

Pingers are also a measure to reduce the environmental impact of sound. These are devices that transmits acoustic signals underwater that scare away marine life before construction commences, so avoiding harm.

Lastly, there has also been suggested to cover the pile driving area using a sound-protected method, to reduce the sound volume. A curtain of bubbles applied on the pile has shown to halve the sound. However, this measure is only applicable to weak water currents [25].

#### *3.2.2.3 Waste management*

About 90% of all wind turbine towers are made of steel which is the main materials of the turbine. Steel can be recycled infinitely and is the most recycled material on the planet. In 2014, 86% of the overall production was recycled [38]. The properties of steel allow it to be continually recycled with no degradation in performance and can be used from one product to another. Construction steel can also be reused without reprocessing. This saves additional greenhouse gas emissions [39].

In order to reduce the amount of material, it is possible to upgrade the steel quality. By upgrading the steel of a wind tower structure, you can achieve great weight savings. One example from the World Steel Association is upgrading from grade S355 to S500, where weight saving of 30% can be achieved. Even though the cost will increase with 20-25% per ton for the higher steel strength it is said that it will lead to a positive balance as 30% less material is needed. Savings will be achieved due to lower transport and construction cost [40].

### 3.2.3 Foundation

#### *3.2.3.1 Process*

To decommission the foundation, it depends on what type it is. Specialised vessels need to be used for the heavy lifting of the foundations. After the removal of J-tubes, access to the foundation is clear. A cutting method is used to take out the J-tubes and to cut the foundation where its decided and will then be lifted. This must be done according to the decommissioning programme.

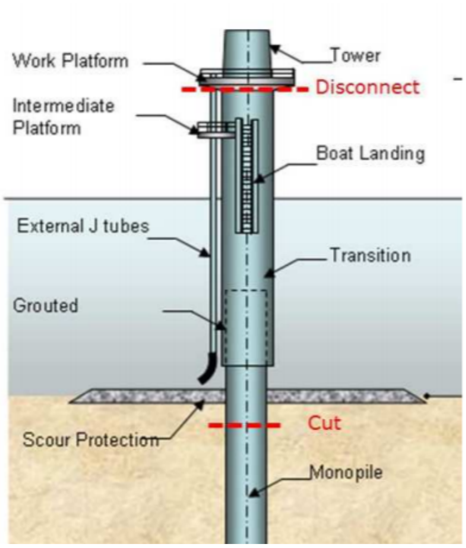


*Figure 20 – Illustration Cutting Monopile*

There are two ways of removal:

- Completely remove the foundation.
- Removing it from where it has been cut under the mud line and leaving the rest as it is without any further disturbance.

Option two is the most preferred because its more convenient economical, less risky and is leaving less disturbance to marine life. Landfilling is necessary to cover the hole after the foundations are lifted. This also depends on what the permits will allow. Usually, the permits require removing it all, but the Energy Act 2004 opens for the possibility of only partial removing if the criteria are met [23].

***Removing Monopile***

First, the pile needs to be inspected, and to decide what lifting attachments are needed. This inspection is done either by divers or Remotely Operated Vehicles (ROV). Then a vessel will be used, this can either be a floating crane, jack up barge or an offshore unit with stabilizing legs. If the pile is covered with a scour protection this needs to be removed first, before the cutting. The crane hooks to the foundation and its cut below the seabed mudline, usually 3-5 meters below, according to the decommissioning programme. Removing the whole structure causes great risks to the environment and the personal, and additionally requires more advanced tools than cutting which makes it more expensive. The cutting methods are either by using diamond wire or water jetting [23].

| Decommissioning concept | Description |
|---|---|
| Partial removal | Substructure with transition piece in one piece cut below the seabed level |
| Partial removal | Substructure and transition piece in separate pieces cut below seabed level and transition piece |
| Complete removal | Removal of monopiles, tripod or jackets with suction buckets by reversing the suction process. Field proven on met mast leaving the seabed unmarked |
| Complete removal | Removal of the monopile, tripod and jacket piles in its full height using water pressure. Novel concept which not yet have been field tested |
| Complete removal | Removal of the monopile in its full height by removing sand around the pile. Considerable impact on the benthic ecologic and challenging. The impact and challenge increase proportional whit the substructure depth |

*Table 5 - Different Methods of Foundation Removal [28]*

In case of full removal of the monopile from the seabed, there are several projects working on innovative concepts for decommissioning wind farms. They are not commercialised yet, but the uncertainties in the requirements of regulations are forcing innovations to be developed [42].

The project Hydraulic Pile Extraction Scale Tests (HyPE-ST) is one example and they are studying the option of removal of offshore wind turbine monopiles in a sustainable way. The HyPE-ST project aims at developing innovative and smart technology to remove the entire monopile in order to make it possible to recycle the steel. Currently, as discussed, offshore piles are removed by cutting them off metres below the seabed, which leaves behind tonnes of steel buried in the seabed. This project is based on a method that does not involve any underwater cutting but is based on hydraulic extraction. The pile is sealed, and its void volume is pressurised using a fluid, e.g. seawater. The pressure will drive the pile upward, liberating the pile out of the soil [43].

#### 3.2.3.2 Environment

Hard structures like the foundations from wind farms usually end up as artificial reefs over time. This might lead to species diversity or be a way to encourage it. There are reported a high abundance of fish partly due to increased production and availability of benthic prey species associated with the artificial reefs. The reason for this is that many fish species feed on the benthic animals. The reports also point out the increased biological production due to reduced trawling activities in the area. This shows that offshore wind farm installations might be an enhancement. In addition, for some vulnerable species, this might also serve as a protected area.

The scour protection that is used for the turbine to prevent seabed erosion can also be adapted for the marine life in terms of foraging and as refuge. This will enhance the species viability. In addition, placing additional reefs might also improve marine life and reduce the distance to other reef habitats [25].

#### *3.2.3.3 Waste management*

The monopile foundation, as well as providing the support structure, is also made from steel which makes the foundation easy to recycle in a similar manner to the tower. AF Offshore Decom have a custom-built environmental base in Vats, in Norway that will handle waste from marine installations. The steel is chopped into manageable sizes and further melted.

The foundation can be of other material than steel. For example, the foundation of Vindeby that uses gravity-based structure which is a concrete based construction. When it was decommissioned the foundation was scrapped and used as new gravity-based foundations and used to make bridges [43]. The use of steel is, however, preferred as it will not lose its quality once from recycling which is not the same for concrete structures. Instead of recycling the concrete its rather a downcycling as the secondary use is not the same value as the first [44].

### 3.2.4 Cables

#### *3.2.4.1 Process*

Subsea cables consist of the array and export cables. When it comes down to decommission of the array cables there is a question to whether to leave them at the site, partial, or fully remove them. If they are left in place the cable ends will have to be buried or cut off. They will also pose a long-term liability as they lay here and needs, therefore, to be monitored. If they are removed, a similar technique used for cable installation can be used. This method involves jetting or ploughing or a combination of these. For some areas with soft soil pulling the cables with enough force might be the solution [4].

With the average of two cable ends at each turbine connecting to the rest of the farm, the option to remove them all might be more prudent in the long term. This will also reduce the liabilities. Another consideration is what to do with the stretches of the cable that are buried under the scour protection. In this case, the option comes down to leaving them in situ or removing both the cables and scour protection. On the reverse side of the scour protection a new marine habitat might have formed, providing as a shelter for marine life here. Therefore, the best option might be to also leave these in situ to avoid the harm it causes to remove it. This comes all down to what the permits allow and what is the most convenient and efficient way [4].

For the export cables, the best case is to leave them in situ. They are buried much deeper than the array cables and therefore removing would cause too much environmental damage, as well as the extreme cost involved with it [4].

#### *3.2.4.2 Environment*

As mentioned, the cables are buried to reduce the threat to the environment and pollution from exposed cables. This need to be monitored to make sure that cables remain unexposed to avoid the possibility of the contamination of the metals [20]. Removing all the cables could cause more damage to the environment because of the disturbance to the seabed [23].

Also, during the operation the cables will emit electromagnetic fields as a result of transmitting the produced electricity. According to an article form Aquatic Biosystems, this might affect the movement and the navigations of the marine life that are sensitive to the electromagnetic fields, such as sea turtles [11].

#### *3.2.4.3 Waste management*

The discussion around the cables has been to leave them in situ to reduce the environmental impact and the high cost. However, the cables are very valuable, and it might be financially beneficial to pull them up from the seabed. Large parts of the cable may be refurbished and reused in other sectors. The cable conductor made from copper can be reused. The cross-linked polyethylene (XLPE), used as electrical insulation in the cable may be cleaned dried and ground and recycled as filler for new cables. It can also be used as an isolation in lower voltage cables [26].

The cables are usually made from a variety of different materials to be able to withstand the rough sea conditions. This also makes them more complicated to dismantle for recycling. The solution to this is to deliver the cable equipment to a company that separates the different parts, like metal which will be recycled, plastics which will be incinerated for energy recovery and finally the toxic materials, which will be disposed [37].

Copper is also a part of the cables. Copper is easy to recycle, and the cooper scrap is divided into both new and old scrap. Old scrap is derived from products that’s no longer in use like disuse electrical cable and old pipes and taps. New copper scraps are derived from off-cuts of products made in the industries. Recycling cooper is also beneficial for the environment. Dangerous emissions like Sulphur dioxide which happens during cooper extraction will be avoided [37].

Lastly, the cables consist of aluminium. Aluminium is easy to recycle and does not degrade during the process. The recycling is effective both environmentally and economically and have many areas of applications [46].

## 3.3 Case studies

Up until this day, there have only been few cases where offshore wind farms have been decommissioned. The table below shows the farms that has been decommissioned. Some of them only consisted of one turbine as a research project, and for the farm Robin Rigg', two turbines were decommissioned because of malfunctioning. Therefore, the case studies focus on commercial operating farms.

| Wind Farm | No. Of Turbines | Total Capacity (MW) | Foundation | Country | Year of Decommissioning |
|---|---|---|---|---|---|
| Utgrunden | 7 | 10,5 | Monopile | Sweden | 2018 |
| Vindeby | 11 | 5,0 | Gravity based | Danmark | 2017 |
| WindFLoat Phase 1 | 1 | 2,0 | Floating | Portugal | 2016 |
| Lely | 4 | 2,0 | Monopile | Netherland | 2016 |
| Hooksiel | 1 | 5,0 | Tripile | Germany | 2016 |
| Yttre Stengrund | 5 | 10,0 | Monopile | Sweden | 2015 |
| Robin Rigg | 2 | 6,0 | Monopile | The UK | 2015 |
| Nogersund | 1 | 0,2 | Tripod | Sweden | 2007 |

*Table 6 – All Decommissioned Projects by 2019*

Yttre Stengrund was the first wind farm to be decommissioned. It was commissioned in 2001 in Sweden and consisted of 5 turbines of 2 MW. It was decommissioned in 2016. The wind farm was delayed by a month due to bad weather. The foundations were cut off in level with the sea bed. When it comes to the environment, Vattenfall stated that this was done according to the environmental authorities. The goal was to restore the site in such a way that any trace the farm will be negligible. The cables were also removed.

The possibility for repowering was an option for Yttre Stengrund, but according to the project manager Maya Hassel, the turbines were an early model. There were only produced about 50 units of this turbine, and therefore there were difficulties getting spare parts for the upgrade. Along with the huge costs with repowering the decision was to decommission the wind farm [47]

Vindeby, in Denmark, was the first offshore wind farm to be installed and consisted of 11 turbines, each on 450 kW. It was decommissioned in 2017 after 26 years of service [48]. Leif Winther (Ørsted Energy) was responsible for the decommissioning. In an interview [49], he said that the process was done according to the plan, but unexpected problems with a large volume of concrete that had been used in the foundations. This delayed the whole decommissioning process by two months. He was unable to tell anything about the financial aspect of it but said that the removal of the foundations was significant in terms of the economics. The foundations used for Vindeby was gravity based which differs from the removal process of a monopile and is more expensive. But then again was less expensive to build [20]. Vindeby was dismantled by removing one blade first, and then nacelle with rest of the two blades, then finally the tower. The cables were directly pulled from the seabed, and the foundations were cut into smaller pieces [49].

Vindeby was considered for repowering, but since the small size of the farm made the whole project for this not economically feasible. Most of the turbines, like cables, foundations and blades were operational but it needed increased maintenance. The gearbox required removal along with maintenance on the i.e. corroded flange bolts. That is why it was not feasible given the size of the turbine, power prices and the cost of the overhaul [49].

In terms of repowering, Leif indicated that if one were to consider repowering with higher output devices, the only thing that was eligible for reuse was the substation and the export cables (up to the maximum capacity of the original wind farm). The rest, like the foundations and the inter-array cable, had to be upgraded to handle the bigger units [49].

When it comes to the environmental impact Vindeby had to remove everything. But according to Leif Winther, there are several organisations working towards the possibility of leaving structures in situ, to avoid environmental damage, but also to reduce the costs [49].

Last year the offshore wind farm Utgrunden was decommissioned. Utgrunden was located in Sweden and consisted of seven turbines with a total capacity of 10,5 MW [50]. The project manager of the decommissioning, Magnus Jansson told that the originally plan for Utgrunden was repowering. The idea was to remove the turbines and keep the monopiles for the upgrade. However, since the farm was built in 2 000 the existing grid connection were to small and the monopiles would be too weak, therefore it was concluded to decommission the wind farm. According to Jansson the market is developing at such rate that repowering of old wind farms would be rare because it would not be economically feasible [51].

The decommissioning was executed in line with the environmental requirements and the foundations and both array and export cables were removed according to the permits. The monopile were cut 1 meter below the seabed [51].

The offshore wind farm Lely, in the Netherlands, was decommissioned after 22 years of service. The farm consisted of four 500 kW turbines. The decision to decommissioned was mostly motivated when a rotor of one of the turbines fell into the water in 2014; the reason for this was metal fatigue. Coupled with this, the farm was at the end of its commercial life and therefore also less profitable [52].

## 3.4 Decommissioning Costs

This section will look at the cost and cost estimations for an offshore wind farm. Since the decommissioning process is taking place offshore and have only been done a few times before, there are a lot of unknown costs involved. This should be taken into consideration before the installation starts. These prices are expected to reduce once the industry gains more experience in the field [23]. All calculations are done on the reference wind farm, unless stated otherwise.

### 3.4.1 LCOE

The economic aspect of wind power and energy production is measured from in the industry´s standard, levelized cost of electricity (LCOE) [53]. LCOE is defined as the revenue required to earn a rate of return on investment equal to the discount rate over the life of the wind farm. LCOE focuses on Life Cycle Cost (LCC), and Life Time Energy (LTE) and gives an indication of what price a project can produce its electricity in kWh/GBP [54].

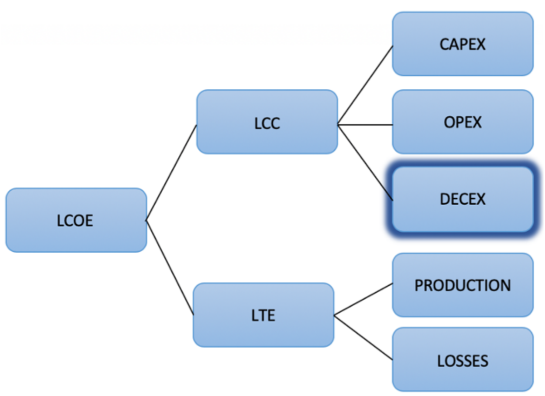


*Figure 21 - LCOE Breakdown*

### 3.4.2 LCC

Life Cycle Cost is a structured approach which addresses all the elements of the cost related to any facilities and can be used to produce a spend profile of the facility over the anticipated lifespan. It takes all cost of acquiring, owning and disposing of a wind facility into account [55]. The costs can be divided into Capital Expenditure (CAPEX), Operational Expenditure (OPEX) and Decommissioning Expenditure (DECEX) [53].

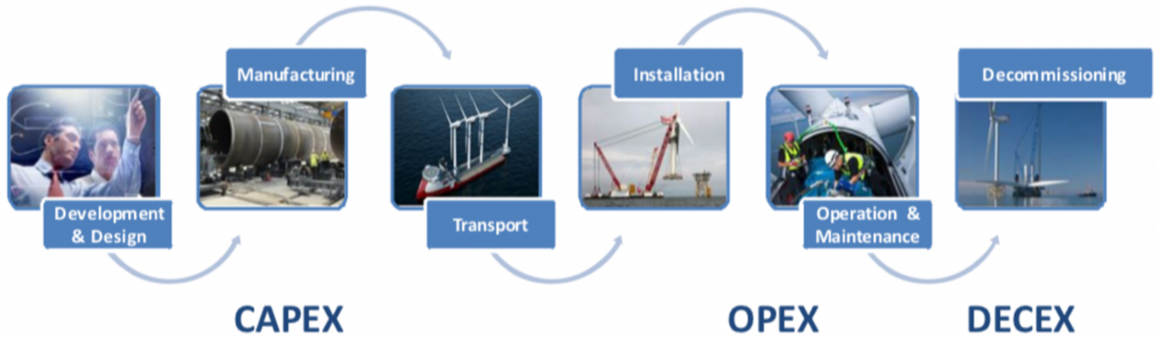


*Figure 22 - LCC Breakdown [53]*

### 3.4.3 CAPEX

Capital expenditure (CAPEX) – Cost incurred in the development and installation of a wind farm up to the works completion date. This includes the cost of obtaining planning approval and project management, the turbine, balance of plant, electrical interconnection, installation, and contingency.

### 3.4.4 OPEX

Operational expenditure (OPEX) – Costs incurred after the works completion date, including operation, maintenance, service, and transmission charges.

### 3.4.5 DECEX

Decommissioning expenditure (DECEX) – The net cost of removal or waste management of all components at the end of the wind farm´s operational life. The cost for decommissioning can be divided into decommissioning of the turbine, foundation, cables, and substation. This thesis will only be focusing on the decommissioning cost and how this cost can be estimated.

In this section the focus will be to compare the DECEX to other known costs, and in that way make some factors that can be used for future references.

Based on available data a breakdown estimation made of the various costs related to decommissioning have been calculated. These numbers are compared with factors like the LCC, installed capacity in MW, and CAPEX. All numbers are calculated on the base of the example park on 1 GW. The park consists of 100 turbines, each on 10 MW. The calculations include all costs related to decommissioning (gross, excluding the resale value of the components). All calculations are attached as attachment 2.

Based on the numbers from BVG the estimated of the total decommissioning cost is 300 million GBP for the reference wind farm. This corresponds to a decommissioning cost of 300 000 GBP per MW. As shown in Table 7 and Figure 23 the costs are divided into Turbines, Foundations, Cables, and Substation.

| DECEX - Decommissioning Cost Brakedown Estimation | |
|---|---|
| Turbine | 40 |
| Fundation | 70 |
| Cable | 140 |
| Substation | 50 |
| Total DECEX | 300 |

*Table 7 - Decommissioning Cost Breakdown Estimation*

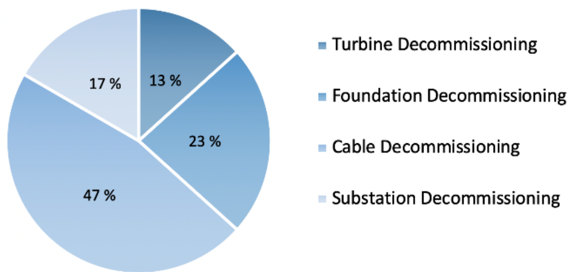


*Figure 23 - Decommissioning Cost Breakdown Estimation in Percent*

DNV GL has made estimation based on installed power capacity, and recently quoted installation cost. Both estimations are made in pairs of two, a high and a low estimation. DNV GL states that the variation of water depth, distance from shore and the total size of the wind farm will make the costs vary too much to only make one estimation. For the reference wind farm, it is assumed that the reference park is close to the lowest estimation, regarding the water depth and distance from shore.

DNV GL´s estimations based on installed capacity range from 255 000 GBP to 425 000 GBP per MW. The estimation from BVGs data is within this range. The low and high estimation based on the recently quoted installation cost is respectively estimated to be 60% and 70%.

Based on these numbers and the reference farm, there has been made estimations for the total decommissioning cost. As seen in Table 8 the estimations range from 255 million GBP to 425 GBP.

Since the highest estimations from DNV GL is based on a greater depth and a further distance from shore, the highest estimations can be excluded from the calculations on the reference farm. The estimated total cost will therefore be between 255 to 329 million GBP, equal to 255 000 and 329 000 GBP per MW.

| **Total Decommissioning Cost** | Millions GBP |
|---|---|
| Estimated Cost - BVG | 300 |
| Cost per MW, Low - DNV GL | 255 |
| Cost per MW, High - DNV GL | 425 |
| Cost of Recently Quoted Installation Cost, Low - DNV GL | 282 |
| Cost of Recently Quoted Installation Cost, High - DNV GL | 329 |

*Table 8 - Estimated Total Decommissioning Cost per MW*

With the data from BVG, it is also possible to make an estimation of how big part the DECEX will be compared to other costs. Figure 24 looks at the total LCC and it is estimated that the DECEX will be 1,46% of the total LCC.

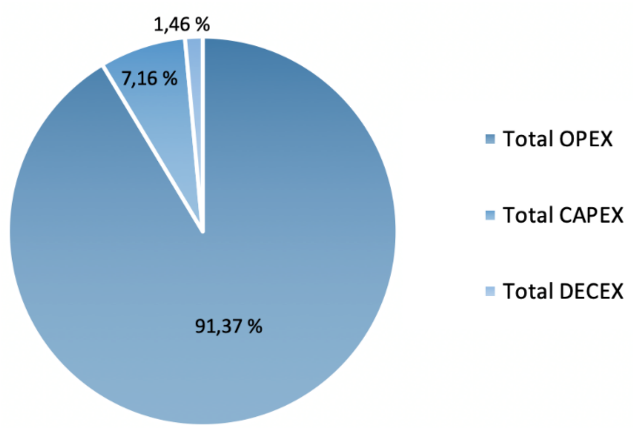


*Figure 24 - LCC Breakdown*

**Error! Reference source not found.** does also include the decommissioning cost in the percentage of CAPEX and Installation Cost. DNV GL estimated a decommissioning cost of 60% to 70% of the installed cost. With the data from BVG, it is estimated to be 63,84%.

| **Key Numbers Example Wind Farm** 1000 MW | |
|---|---|
| Decommissioning in Percentage of Installation Cost | 63,83 % |
| Decommissioning in Percentage of CAPEX | 20,41 % |
| Decommissioning in Percentage of LCC | 1,46 % |

*Table 9 - Key Numbers Example Wind Farm*

IRENA has done some calculation on the past, today´s and the future total DECEX compared to the LCOE. It is important to notice that these numbers are not to be compared with the calculations of decommissioning as a percentage of LCC. The following two diagrams show an LCOE breakdown for a typical commissioned offshore wind farm in 2001 and 2015. DECEX is included, which in this example is set to be 0,4% and 0,5% of the total cost. DECEX did increase by 25% in these 14 years. The reason for this may be the current uncertainty of decommissioning and the lack of experience [12].

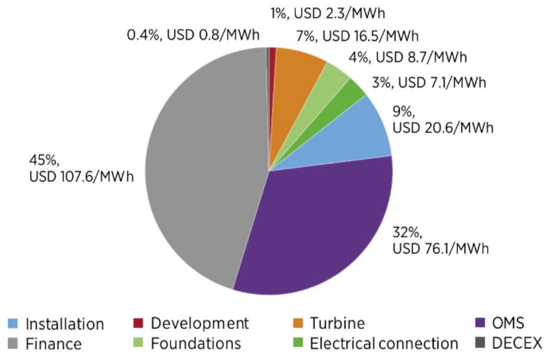


*Figure 25 - Contribution of each element to cost of energy for typical project commissioned, end-2001 [12]*

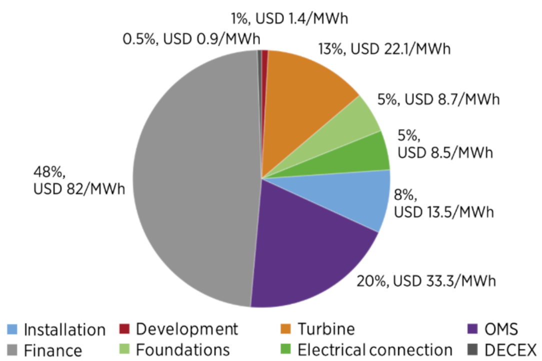


*Figure 26 - Contribution of each element to cost of energy for typical project commissioned, end-2015 [12]*

It is anticipated that the DECEX will decrease in the years to come. Figure 27 shows the LCOE breakdown by 2030. Based on the potential for further innovation and new technology, the decommissioning cost is estimated to decrease approximately 45%. It will be a larger part of the total LCOE, but since the total cost will get a reduction, and the energy production will increase, it will still be cheaper than today.

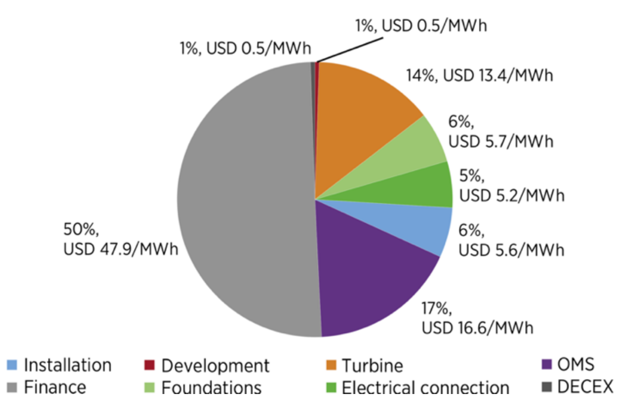


*Figure 27 - Breakdown of LCOE by element in 2030 [12]*

## 3.5 Experience from the Oil and Gas Sector

The offshore O&G industry is experienced in developing innovative structures and foundation concepts in the marine environment. This chapter focuses on how experience from the offshore O&G industry can be used in the offshore wind sector.

Wind turbines and O&G platforms use different technologies, but both involve some form of decommissioning at the end of their lifetime. Both sectors make use of similar structures, such as cables, monopile, and gravity-based foundation. In addition, they may operate in challenging sea- and weather conditions and be experienced in different seabed types. Techniques from the decommissioning of offshore O&G platforms have been adopted in the wind sector. O&G installations have been decommissioned since the 1990s and some of the techniques that can be adapted to the offshore wind industry are heavy lift techniques and removing / cutting of piles. Significant differences with the offshore wind industry will, however, strongly influence the decommissioning costs, making it challenging to compare the cost between the two sectors. For example, according to the UK Department of Energy and Climate Change, well abandonment accounts for as much as 60% of O&G decommissioning costs, seen in Figure 28 [56][57].

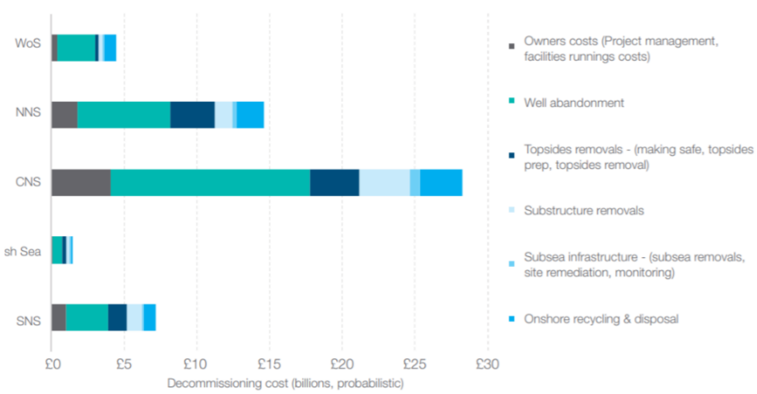


*Figure 28 – Decommissioning Cost Distribution by Category on Different Platforms [57]*

O&G installation are often hundreds of kilometres from shore, whereas offshore wind farms are generally closer to land, typically less than 100 km. In addition, O&G installations are normally in hundreds of metres of water, compared with typically 10 to 50 metres water depth for bottom fixed offshore wind farms [58].

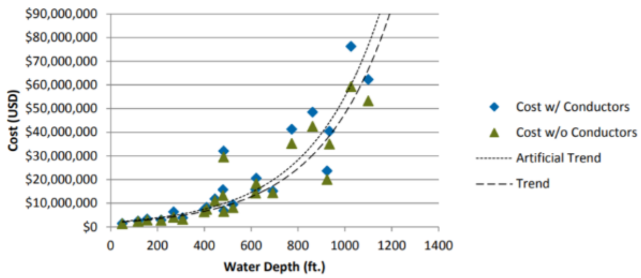


*Figure 29 – Estimated Platform Decommissioning Cost [59]*

Figure 29 illustrates the estimated increase in decommissioning cost for O&G installations as the water depth increase. It can be assumed that it will be a similar approach for offshore wind turbines. The decommissioning cost for farms in deep water will be higher. As foundations are improved as well as the floating anchor system becomes more cost effective, it will be taken advantage of sites in deeper water, which means higher cost [59]

### 3.5.1 Different cutting methods

Most of the structures in the O&G sector require underwater cutting to be decommissioned. Such methods and contingent equipment have been developed in the last decades, to meet requirements of O&G decommissioning. Structures in the O&G sector normally do not exceed 3 meters in diameter. The distributed load on a platform is better supported with multiple piles. However, the diameter of a monopile foundation used for wind turbines is normally between 6 and 10 meters. That means that the techniques that are used on platforms must be able to be scaled up to be suitable for monopile cutting in the wind sector. For offshore wind decommissioning, customized tooling would be developed, to fit piles of greater diameters [56].

Two techniques that often are used are abrasive water jet cutting and diamond wire cutting. These are methods that can be adapted in the offshore wind sector as well. These methods will be presented and discussed further with examples and statement from the industry.

### 3.5.2 Abrasive water jet cutting

Ultra-high pressure (UHP) abrasive water jet cutting uses water at pressures of up to 3 000 bar fired through a nozzle, forming a water jet. This cutting technique is used for pile removal in marine environments and the method works both over and under water. The method and equipment are continually being developed to use larger piles, and for using ROV rather than divers. Even though it is used for diameters up to five metres in the O&G sector, in principle it can be scaled up to the pile diameters and wall thicknesses required for offshore wind monopiles, according to the report [56]. For this cutting method, the pile can be cut either externally or internally, it depends on the ease of removing seabed material down to the level of the cut and the access to the pile wall.

An internal cut would be preferred as the internal pile cutting system enables the possibility of cutting cut off piles below sea level. This avoids the need for costly underwater excavations around the circumference of the pile [58].

*Figure 30 - Abrasive water jet cutting [56]*

The abrasive water jet method can easily be adapted to the offshore wind sector, as it uses the same cut for all diameters and thickness. It is the thickness of the pile that will dictate the length of the time it takes to make the cut. The cutting time using UHP abrasive jet cutting depends mainly on the circumference of the pile and on the wall thickness, as well as the pressure of the water jet. The speed of the nozzle needs to be slower for thicker material, says Mark Weeks, Sales and Marketing Manager in RGL Services. He also mentions that the workers are away from the workface and the equipment is semi-automated which means no risk for employees [60].

### 3.5.3 Diamond wire cutting

Wire cutting is a preferred method for cutting cables in challenging conditions for divers, because this method also can be set up from an ROV (remotely operated vehicle). According to the report diamond wire cutting is less suitable for monopile cut as jamming of the wire is a potential risk when the cut is horizontal, especially with greater diameters. For offshore wind decommissioning, diamond wire cutting might be selected for cutting the array cables instead at their exit from the monopile [19][60].

*Figure 31 – Diamond Wire Cutting Illustration [19]*

Diamond wire cutting includes many advantages. The diamond wire can be wrapped around almost any size or shape and it is a cost-effective method, according to the report; *Sustainable decommissioning of an offshore wind farm*. However, one of the challenges is the fact that it requires good access to the cutting area [23].

### *Example of cutting*

RGL Services executed removal of a mast pile in Denmark. They performed an abrasive water jet internal cut on a pile of 1 800 mm diameter and 45 mm thickness. Water depth was approximately 14 meters and the cut line was set to 24,2 meters from the top of the pile. It took 8 hours to complete the cut before it was successfully lifted from the water. There was no requirement for divers to be used, and all operatives were remotely situated from the works reducing the chance of accidents. Diamond wire sawing had originally been attempted to remove the pile. The attempts were visible, as you can see in Figure 32, and proved unsuccessful.

*Figure 32 - Diamond Wire Cutting attempt not Successful on Vertical Pile [61]*

Magnus Jansson, Project Manager in Vattenfall, was responsible for the decommissioning of the offshore wind farm Utgrunden. It was used internal water abrasive cut to remove the monopiles. The cut was done below the seabed level, leaving some structures left in situ. Vattenfall were allowed to do this, regarding the permits. Jansson tells that it is more realistic to leave in situ, as removing the whole pile is a costly operation [51].

### 3.5.5 Current status of Oil and Gas Installations in the Northern Sea

By 2014 was only 12% off all North Sea installations have been decommissioned by this date. Although this equates to over 150 structures already decommissioned in the Northern Sea [62]. Data from OSPARs database in 2015 over O&G platforms in the Northern Sea was collected where an interesting observation was made. All Northern sea installations marked either *Closed Down* or *Decommissioned* was added in a diagram. The result showed that there are almost as many closed O&G installations, waiting to be decommissioned compared with ones who already have been decommissioned [63].

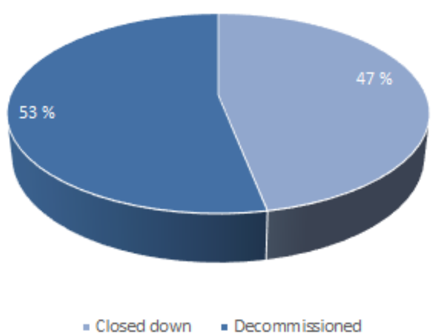


*Figure 33 – O&G Platform, Currrent Status, North Sea [63]*

The analyst Markus Nævestad in Rystad Energy says that the oil companies often postpone decommissioning of the platform after it is closed. As long as the platform is clean and free from carbon emission operators leave the installation for several years. In many cases, it has been caused by a period of low oil prices, and they cannot afford the cost of decommissioning the installation [64]. If the field is consisting of several installations, they might bundle up and they do the final removal when the whole field is closing. AF Gruppen Offshore Decom AS mention that they were decommissioning a platform closed in 1972, but it was not removed until 2009. At this point, it was necessary to spend millions due to the bad condition, and it had to make sure that the platform could be safely removed. This trend could possibly be the case for the offshore wind sector as well. To avoid this, it is the government's responsibility to introduce laws and regulations [65].

### 3.5.5 Vessels

Specially designed ships have been continuously developed for the logistical servicing of offshore and subsea installations. It involves installation, maintenance and decommissioning of the offshore platform. This experience has been transferred to meet the demand for offshore wind vessels. Table 10 include some of types of vessels that have been developed for the decommissioning in offshore wind market [29].

| Vessel type | Description |
|---|---|
| Jack-up barge | Barge or platform equipped with legs and a jacking system allowing the barge to self-elevate when operating. Used for installation of blades, hub, nacelle and tower. The components are transported to the site by a barge. |
| WTIV | Purpose build jack-up vessel for the installation of blades, hub, nacelle and tower. WTIV is self-elevating similar to a jack-up barge but transports the components on its own deck. |
| Heavy lift vessel (HLV) | Designed to lift very large loads and used for installation of topsides and substructures. There are several types and variations of HLV e.g. floating sheerleg cranes, monohull crane vessel, catamaran cranes, semi-submerging vessels lifting without the use of cranes. |
| Semi-submersible crane vessel (SSCV) | Designed with increased stability allowing very large crane capacity. Used for topside installation. |
| Barge | Capacious flatbottom vessel used for transportation of wind turbines, substructures and OHVS topsides etc. |
| Cable laying vessel (CLV) | Used for cable recovery by pulling the cable on drums or turntables. |

*Table 10 – Different Types of Vessels [29]*

The size and weight of the turbine will determine the lifting capacity and vessel's deck space. Vessels are being designed to be suitable to install and decommissioning the increase in size of turbines. Semi-submersible and jack-up crane vessels with enhanced capabilities are now becoming available, to serve both O&G decommissioning and offshore wind sector. As the turbines are becoming bigger, the vessels are forced to become larger and developed to handle the length and the mass of every component [29].

Fred Olsen Wind Carrier was established in 2008 to meet the increased demand for offshore wind vessels. In May 2019, they were awarded a contract by MHI Vestas Offshore Wind for the installation of 100 turbines, each on 9,5 MW [66].

Even though vessel is being developed for the offshore wind sector, the lack of available vessels to suit a current project might be an issue as the demand for vessels in the offshore wind market will increase. Kim Madsen, from Momentum Gruppen A/S was interviewed about the repowering project Bockstigen in Sweden. Everything seemed to be done according to the plan. Still, the project was delayed because of the Jack Up Rig meant for this project had to finish work in Finland [67].

O&G installations are essentially single entities, while at an offshore wind farm, there are multiples of installations/decommissioning operations that are identical. This is leading to different decommissioning logistics. Cost savings can be realised using efficient strategies and technologies. Johannes Thrane from AF Offshore DECOM AS adds that the vessel rent is the biggest cost, regarding time, weather downtime and mobilisations costs. There is room for logistics improvement to reduce the cost significantly. Vessel could be further improved to be loaded with a bigger number of components compared to today's capability, in order to reduce the number of trips to the shore [65]. On the other hand, the daily rate for a vessel is more expensive, the bigger and more effective it is. That means that it is important to consider whether to choose the biggest one available. This was the case for Utgrunden. Magnus Jansson says that very project is individual, there are several factors that differ from project to project; where it is located, the size and the capability of handling the crap material. It is either possible to use a smaller vessel, going back and forth to shore. A larger vessel means that it can be load more on it, meaning less travel. It is important to find the balance point between time and cost, compared to a big vessel [51].

The vessels used in the O&G sector has been developed to lift heavy installations in one single lift if possible, in order to reduce the number of marine operations. In general, the aim should be to minimise the number of separate marine operations to be the most efficient. According to WindEurope´s report it is possible to reduce the cost when reducing the number of lifts in the decommissioning process [68].

***Vessel day rate***

Vessel day rate can have a great influence on the total decommissioning cost. DNV GL mentions that the vessel cost is significant where typically two-thirds can be spent on specialist vessel in the removal operations. It is, however, hard to predict because of the market forces. The day rate can vary depending on what time of the year, demand, contract lengths and macroeconomy. The decommissioning cost will be highly dependent on the vessel rates available at the time of decommissioning and how many available vessels there are fitted for the project [69].

The market uncertainty has been regularly seen in the O&G vessel market. Figure 34 demonstrates how rates for offshore vessel varied from 2007 up until 2015 [69].

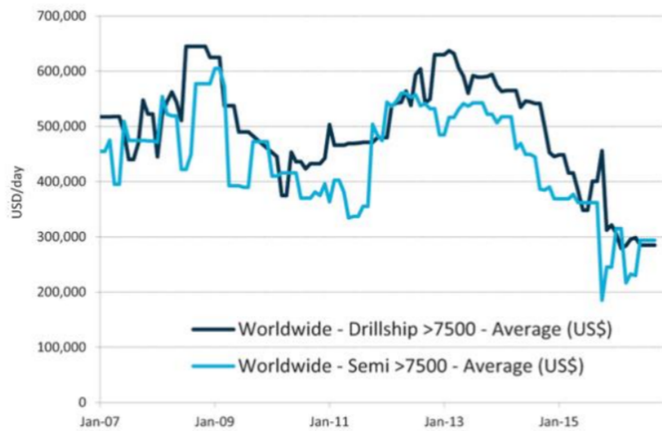


*Figure 34 – Variation Day Rate Vessel [69]*

In the short term, the market is extremely volatile, where the highest and lowest rates vary around 300%. In addition to the market forces, the cost is highly influenced by mobilisation, location and work scope [69].

# 4 Repowering and Lifetime Extension

## 4.1 Repowering

Another solution when a wind farm is reaching its lifetime is repowering. Repowering is a type of decommissioning where the purpose is to upgrade the wind farm with better efficiency and reusing whatever parts that are left. In this way, capital costs can be reduced [23].

Repowering can be done in two following ways:

- *Partial repowering*: Installing minor components like rotors, gearboxes, blades, power electronics and or towers.
- *Fully repowering*: Replacing old turbines with bigger and newer units. This might require bigger foundations as well because of the much heavier structure.

This decision often comes down to factors like the site, whether spare parts are available, the costs, and if there is expected profitability [23].

### 4.1.1 Electrical infrastructure

The electrical cables have a lifetime exceeding far than the other components of the wind farm, making these eligible for re-use. Therefore, it might be interesting to look at investing in higher capacity cables in the design phase of the wind farm. This way, since the cable has a longer lifetime than the wind farm, will be easier for re-use. This investment would increase the capital cost, but in the long run, this might be economically feasible when it comes to repowering the farm. Being able to reuse the cables along with the substation, the cost of engineering the electrical infrastructure with repowering can be reduced by 90% [70].

This aspect is important in the planning phase of the farm, but when it comes down to foreseeing the future and the development in the industry this might make it harder to execute in real life.

### 4.1.2 Support structure

The turbines' lifetime is estimated to be from 15 – 20 years. With foundations that could last much longer, this would present an easy-to-replace possibility. However, as the technology improves, and the turbines get larger, the foundation that is already there will be too small to handle the new units. In addition, the infrastructure will also make the new turbines too closely spaced for each other in terms of the wake effect. This development is most uncertain and that is why it is difficult to plan for repowering.

The foundation lifetime is normally 25 years. For older wind farms it is less because of the weak corrosion protection. However, in newer generation wind farms the foundation could last up to 35 years because of specific corrosion systems are employed [70].

### 4.1.3 Operation & Maintenance

From an operation and maintenance perspective repowering is a very attractive option. As components age, the technology advances, meaning repowering will require lower maintenance. Offsite maintenance assessments, health monitoring are common factors here, and will result in lower costs and less risks for the personnel involved [70].

### 4.1.4 Case study

Recently what was said to be the first repowered wind farm took place in Sweden. Momentum Group, a Danish firm was the one responsible for the project. They recommissioned the wind farm called Bockstigen which consist of five turbines. The farm was commissioned in 1998 [71].

The partially re-powering included removing the nacelle, blades and controls system. In this way, Momentum Gruppen A/S was able to reuse the original turbines, foundations and transmission cable. This resulted in the extending of the lifetime of the wind farm by another 20 years and the expected annual electricity generation went from 5 000 MWh to 11 000 MWh. The total cost of the repowering was 5,6 million dollars. The reuse of the cables, foundations, and towers here show that with the right maintenance they could last another 15-20 years [67].

The repowering did not require any new permits. Because there was not any change in the site or the hub height, the repowering was considered as a major repair on old turbines by the authorities. According to Madsen, the requirement of a new building permit would have made the project impossible [67].

***The Future of Repowering***

The problem with repowering according to Giles Dickson, CEO of the trade group WindEurope, is that the technology is too soon. The technology is at a stage whereby generational design changes are significantly large as to render 20-year-old designs. However, repowering as a solution is up for consideration for many of the producers. The problem is not that the first-generation turbines are aging, but more the fact that the advances in the turbines have been so significant over the years. This has led more to the mindset of upgrading the wind farm to bigger units to get a bigger revenue instead of refurbishing the small existing wind farms [72].

Andrea Scarsola, who is a senior market analysist for wood Mackenzie power & renewable also agrees that it is too soon in the maturity of the technology. But for small sized turbines, this is ideal means of extending the lifetime of the wind farm. But for the bigger projects, it's still too early, even in developed markets like Germany and the United Kingdom [72].

## 4.2 Lifetime extension

Many wind farms are now reaching their design lifetime of 20 years [73]. As a measure to postpone decommissioning, lifetime extension is an alternative to repowering. To extend the lifetime the turbines need to have a sufficient lifetime left in a way that the safety level is not compromised with the further operation. To extend a turbine's lifetime from 20 to 25 years, the operators must prove through inspections and operational data that the probability of failure in structural components is still at an acceptable level [74].


*Figure 35 - Lifespan of a Turbine Including the Extension of the Lifetime [74]*

According to Megavind, to verify and ensure the safety the inspections should be done annually on each of the different components. Cracks, corrosion, rust, and dents are all factors that could contribute to reducing the life extension and should be quickly detected and repaired. Every three years there should also be conducted a visual survey of the blades [74].

Many operators are turning to the option of lifetime extension. Recently Siemens Garcia signed a contract to extend the lifespan of a 238 MW farm in Spain from 20 years to 30 years [75]. The reasons for choosing lifetime extension over repowering are in many cases the difficulties with new permits and the high costs involved. The repowering of Bockstigen would not have happened if new permits were required [67].

In addition, there are stricter environmental regulations now than when the farms were commissioned in the first place, and if the operation and maintenance costs are lower than the output of the farm the LCOE will be reduced [70]. These are factors that make repowering more difficult and therefore lifetime extension a more benign solution [76].

When it comes with to the legal requirements of extension, this is based on country to country since there is no international regulations in place. The turbines are certified for their design lifetime, and once this expires, the turbines' provisions are based on which country to set the requirements for safety of further operation. In the United Kingdom, there is no such specific regulation only general approach of ensuring safety on wind turbines [73].

To make it easier for the decision of lifetime extension, standardization of documentation of the farm should be in place. In addition, easier access and more complete data of the design and clearer frameworks which regulates the process would help contribute the safety of the process [76].

The turbine suppliers also play an important part in terms of extension. The understanding of aging mechanisms over time will provide for common guarantees and certifications for the operator and authorities and will strengthen the decision of lifetime extension [76].

# 5 Discussion

The purpose of this section will present the result from the literature studies, calculations and interviews in the previous chapters. The aim of this section is to find out what is the best solution to carry out when a wind farm is reaching the end of its lifetime.

***Permits***

Based on the differences in the regulations and provisions from each country when it comes to managing the decommissioning process, many of the authorities have not kept up with the developing market. A clearer framework should set the standard, from an international point of view, for how to handle every aspect. Everything from the environment to handling the waste, and funding of the project. This would make the process more efficient and reduce environmental impact. In addition, one would avoid the possibility of the burden to be placed on the government in case of an operator´s insolvency.

***Market***

The market analysis clearly shows a positive trend in the commissioning of new wind farms. The farms are expected to grow in both size and numbers. This will reflect the future market for decommissioning of offshore wind turbines. Predictions made, based on available data, shows that from the year 2035 the farms that will be decommissioned will range from 3 000 to almost 7 000 MW yearly, with only a few exceptions. As a comparison, it was decommissioned 16 MW in 2015, 4 MW in 2016, 5 MW in 2017 and 10,5 MW in 2019. It seems clear that the market will have to prepare for tremendous growth in the years to come.

Most of the commissioned and planned wind farms are in countries like The United Kingdom, Germany, Denmark, Netherlands, and Belgium. The market for decommissioning will therefore mainly be in these countries. But France, Ireland, and Poland have several planned projects and will also be big players in the future.

***Decommissioning process***

Up until now, the decommissioning process has consisted of a reverse methodology. As technology improves there will be new tools and new ways to handle the logistics, to improve the efficiency and reduce the cost and risks connected to this. Many operators, from the case studies, choose the decommissioning as an alternative as this would be economically feasible, and is also regulated by the permits that force this action. From the case studies, many of the wind farms were too small to be repowered, which resulted in the decommissioning.

***Environmental Aspect***

In order to understand the site of a planned wind farm, there should be conducted environmental surveys. This will help to reduce the impact of the wind farm and preserve the existing life her. Several measures like the *easy start* method and Pingers which warns the fish before construction will reduce the noise impact a decommissioning process inflicts.

On the reverse side, wind farms also have a positive impact. The wind turbines turn into artificial reefs over time. The decision to leave the foundations and cables or to remove it has been an issue when it comes to decommissioning. This comes down to what the permits will allow, but from an environmental perspective, the option to leave it would cause less disturbance to the seabed.

***Waste Management***

Based on the waste hierarchy, reusing the turbines after its lifetime is the most preferable option. This results in the turbine being used further than its design lifetime, or as spare parts for maintaining other operating wind farms. If that is not possible, the wind farm should be recycled. Most of the parts have several ways of being reused or recycled, however, the blades present a difficulty.
The blades can be, as described in chapter 3.2.1, be reused as spare parts, artificial reefs, or as building materials for creative projects like a playground or street furniture. These solutions have been dealing with some of the waste, but they will not be sufficient when the numbers of decommissioned wind farms increase. The reason is that most of the projects are only using a couple of blades, and farms with more than 100 turbines would have more than 300 blades to decommission. The importance of a good recycling process is therefore essential to make the waste management environment-friendly.

***Cost***

The cost analysis shows that the total cost of decommissioning will vary a lot depending on the distance from shore, water depth, and other variables. For the reference farm, it is calculated that the decommissioning cost would be between 255 000 to 425 000 GBP per MW, but that it most likely will be around 300 000 GBP per MW. It is also calculated to be between 60% and 70% of the installation cost, with a high probability of it to be in the lower range between 60% and 65%.
Lastly, an LCC breakdown was calculated based on available numbers. These calculations estimate the DECEX to be 1,46% of the total LCC.

Due to all the variations such as water depth and distance from shore, it is not possible to give any specific numbers for future decommissioning projects, but the estimates presented can be used as good indicators.

***Experience from Oil and Gas***

The existing cutting methods from O&G must be scaled up to fit in the offshore wind sector. Internal abrasive water jet is preferred cutting technique on monopile decommissioning if it is possible to leave some of the structures in situ. The offshore wind farm Utgrunden used internal abrasive water jet as a cutting method for the monopile foundation, which was done successfully. Diamond wire cutting is recommended when cutting cables.

The rent of vessels is a significant expenditure, which is hard to predict because of the market forces. It is likely that offshore wind decommissioning will be competing with vessels in offshore wind installations projects, O&G projects, and other subsea installations. This is because is expected to see a growth in both the decommissioning market of wind and O&G.

In order to reduce the vessel cost, there must be done some logistics improvement. This means reducing the amount of lifts and to load the vessel with the most effective number of turbines in order to reduce the trips to shore. However, it is important to find the balance point between cost and size of vessels, based on the individual project.

***Repowering/Lifetime Extension***

Repowering should be highly considered after a turbine's lifetime. However, the technological improvement over the last years has made repowering almost impossible to plan ahead of decommissioning a farm. For now, it is not economically feasible because of the increased size of turbines. For many of the case studies, the farms were considered too small to repower.

Once the turbines will eventually reach a certain efficiency, the established infrastructure and the possibility of reusing foundations and cables, will result in repowering as an optimal alternative to decommissioning in the future.

Partially repowering is another option to do, but for many operators, like with the case studies, there were difficulties obtaining spare parts. But if it is possible to do so, this could increase the output of the farm considerably, like with Bockstigen.

Lastly, there is lifetime extension. It will be a good substitute if there are issues with permits and it prevents repowering a site. Maintaining and inspecting will be important in the last years of the turbines to ensure safety, but it will also help reduce the LCOE if it is possible to operate the wind farm longer.

# 6 Conclusion and Further Work

## 6.1 Conclusions

The aim of this thesis has been to undertake an assessment of a decommissioning process considering aspects like the environment, costs, and alternatives to the process. In addition, a market analysis has been conducted to predict the market for the years to come.

The market analysis clearly presents the enormous growth in farms that has to be decommissioned in the future. Both the methods and solutions for decommissioning, and the market for vessels needs to be optimized and ready for a fast-growing market.

The preferred way of decommissioning has been the reverse method of the installation process. One can draw experience from the O&G sector but there are many aspects that cannot be compared. However, many of the cutting techniques can be adapted from the O&G industry. The internal abrasive water jet technique has shown to the best method to use in the wind sector for cutting monopiles.

The vessels used in the O&G sector are also used in decommissioning offshore wind farms. The logistics, however, are different, making the vessels operations in the wind sector hard to compare with O&G cost.

Decommissioning a wind farm will have an environmental impact. Conducting environmental surveys and measure will help prevent this. However, the structures serve as artificial reefs and improve the abundance of fish in the area. The decision to leave some structure will help to avoid the damage done to the seabed due to decommissioning, despite the regulations nowadays prevent this.

Waste management is an important part of decommissioning in order to reduce environmental impact. An offshore wind turbine consists mainly of steel, which is easy to recycle. However, the blades present a challenge. To this date, there are no good solutions for either reuse or recycling, and the blades will often become landfill.

Repowering is an alternative to decommissioning. Based on the case studies, and the market analysis the repowering is at a stage where the technology of it cannot catch up with the development. Another preferable solution to this is lifetime extension of the wind farm. By extending the lifetime, through structured maintenance, the LCOE will be reduced.

## 6.2 Further work

In the future, the decommissioning process should be more standardized. Especially the regulations regarding the funding and removal of the structure. Ways of funding the decommissioning should be in place to make sure that the operator carries the burden. Aligning these provisions for each country would help to ensure this.

The farms in the future should be designed with repowering in mind. When the market has reached a point where the turbine size is stabilized repowering will be a good alternative. Planning ahead of this, before commissioning a farm will reduce the cost of repowering and make the process easier.

Another suggested work for the future is the certification of the turbines. This would simplify the lifetime extension process by setting a standard of how long the extension possible without risking the safety.

It will be important to find a good solution for reusing or recycling the blades. Some companies, like Veolia, are working on several solutions to be able to recover the fibres. This work has to continue to ensure proper waste management of the whole turbine.

# 7 References

[1]"Wind energy in Europe in 2018", *Windeurope.org*, 2019. [Online]. Available: https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf.

[2]"RENEWABLES 2018 GLOBAL STATUS REPORT", *Ren21.net*, 2019. [Online]. Available: http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_-1.pdf.

[3]"Advantages and Challenges of Wind Energy", *Energy.gov*, 2019. [Online]. Available: https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy. [Accessed: 10- May- 2019].

[4] G. Smith, C. Garrett and G. Gibberd, "Logistics and Cost Reduction of Decommissioning Offshore Wind Farms", 2015. [Online]. Available: https://www.researchgate.net/publication/274896458_Logistics_and_Cost_Reduction_of_Decommissioning_Offshore_Wind_Farms.

[5] C. Desmond, J. Murphy, L. Blonk and W. Haans, "Description of an 8 MW reference wind turbine", *Journal of Physics: Conference Series*, 2016.

[6] *Lifetime extension of wind turbines*. DNV GL, 2016.

[7] G. Boyle, *Renewable energy: Power for a sustainable future*, 4th ed. Oxford University Press, 2017.

[8] *Statkraft.com*, 2010. [Online]. Available: https://www.statkraft.com/globalassets/old-contains-the-old-folder-structure/documents/wind-power-aug-2010-eng_tcm9-11473.pdf.

[9]"How Do Wind Turbines Work?", *Energy.gov*, 2019. [Online]. Available: https://www.energy.gov/eere/wind/how-do-wind-turbines-work. [Accessed: 2- May- 2019].

[10] *Offshore wind-turbine structures: A review*. Institution of Civil Engineers, 2013.

[11] H. Bailey, K. Brookes and P. Thompson, "Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future", *Aquatic Biosystems*, 2014. [Online]. Available: https://aquaticbiosystems.biomedcentral.com/articles/10.1186/2046-9063-10-8.

[12] *INNOVATION OUTLOOK OFFSHORE WIND*. IRENA, 2016.

[13]"Rentel Offshore Wind Farm | The Project", *Rentel.be*. [Online]. Available: https://www.rentel.be/en/the-project. [Accessed: 2- May- 2019].

[14]"Offshore wind farms: the sea giants", *Iberdrola*. [Online]. Available: https://www.iberdrola.com/top-stories/environment/how-does-offshore-wind-energy-work. [Accessed: 23- May- 2019].

[15] Recycling | WorldAutoSteel", *Worldautosteel.org*. [Online]. Available: https://www.worldautosteel.org/life-cycle-thinking/recycling/. [Accessed: 10- May- 2019].

[16]"Siemens Gamesa launches 10 MW offshore wind turbine; annual energy production (AEP) increase of 30% vs. predecessor", *Siemensgamesa.com*, 2019. [Online]. Available: https://www.siemensgamesa.com/en-int/newsroom/2019/01/new-siemens-gamesa-10-mw-offshore-wind-turbine-sg-10-0-193-dd. [Accessed: 03- May- 2019].

[17]"World's Largest Offshore Wind Turbine | Haliade-X | GE Renewable Energy", *Ge.com*, 2019. [Online]. Available: https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine. [Accessed: 20- April- 2019].

[18] C. Steitz, "MHI Vestas turbine platform can scale up to GE's 12 MW rival: CEO", *U.S.*, 2019. [Online]. Available: https://www.reuters.com/article/us-mhivestas-windfarm/mhi-vestas-turbine-platform-can-scale-up-to-ges-12-mw-rival-ceo-idUSKCN1M41EA. [Accessed: 03- May- 2019].

[19]"Assessment of Offshore Wind Farm Decommissioning Requirements", *Ontario.ca*, 2016. [Online]. Available: https://www.ontario.ca/page/assessment-offshore-wind-farm-decommissioning-requirements.

[20] C. Januário, M. Bell and S. Semino, "Offshore Windfarm Decommissioning: A proposal for guidelines to be included in the European Maritime Policy", 2019. [Online]. Available: https://www.researchgate.net/publication/228636135_Offshore_Windfarm_Decommissioning_A_proposal_for_guidelines_to_be_included_in_the_European_Maritime_Policy.

[21]"DECOMMISSIONING OF OFFSHORE RENEWABLE ENERGY INSTALLATIONS UNDER THE ENERGY ACT 2004", *Assets.publishing.service.gov.uk*, 2019. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/788051/decommissioning-offshore-renewable-energy-installations-guidance.pdf.

[22] S. Kraemer, "Offshore wind farm lifetime extensions: why the 'beyond 2020' energy policy dialogue must start now | New Energy Update", *Newenergyupdate.com*, 2014. [Online]. Available: http://newenergyupdate.com/wind-energy-update/offshore-wind-farm-lifetime-extensions-why-beyond-2020-energy-policy-dialogue [Accessed: 2- May- 2019].

[23] E. Topham and D. McMillan, "Sustainable decommissioning of an offshore wind farm", *Renewable Energy*, vol. 102, pp. 470-480, 2017.

[24] M. Bentin, "Installation, commissioning and decommissioning offshore wind", Germany, 2017.

[25] E. Draget, "Environmental Impacts of Offshore Wind Power Production in the North Sea", *Awsassets.wwf.no*, 2014. [Online]. Available: http://awsassets.wwf.no/downloads/wwf_a4_report___havvindrapport.pdf.

[26]"Guide to an offshore wind farm", *Thecrownestate.co.uk*, 2019. [Online]. Available: https://www.thecrownestate.co.uk/media/2861/guide-to-offshore-wind-farm-2019.pdf.

[27]"Directive 2008/98/EC on waste (Waste Framework Directive) - Environment - European Commission", *Ec.europa.eu*, 2016. [Online]. Available: http://ec.europa.eu/environment/waste/framework/. [Accessed: 1- May- 2019].

[28] P. Andersen, A. Bonou, J. Beauson and P. Brøndsted, "Recycling of wind turbines", *Orbit.dtu.dk*, 2014. [Online]. Available: http://orbit.dtu.dk/files/102458629/DTU_INTL_ENERGY_REP_2014_WIND_91_97.pdf.

[29] W. Ostachowicz, M. McGugan, J. Schröder-Hinrichs and M. Luczak, M*ARE-WINT New Materials and Reliability in Offshore Wind Turbine Technology.* Springer Open, 2016.

[30]"How can wind turbine blades be recycled?", *Living Circular*, 2018. [Online]. Available: https://www.livingcircular.veolia.com/en/industry/how-can-wind-turbine-blades-be-recycled. [Accessed: 2- May- 2019].

[31] J. Jensen and K. Skelton, "Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy", *Renewable and Sustainable Energy Reviews*, 2018.

[32]"home - green ener tech", *windmarket.eu at ranktorank.org*, 2019. [Online]. Available: https://www.ranktorank.org/www.windmarket.eu. [Accessed: 3- May- 2019].

[33]"SECOND HAND WIND TURBINES FOR SALE | SECONDHAND WIND TURBINES | USED WIND TURBINES | RETROFIT WIND TURBINES | REFURBISHED WIND TURBINE | REMANUFACTURED WIND TURBINES", *Repoweringsolutions.com*. [Online]. Available: http://www.repoweringsolutions.com/english/index.htm. [Accessed: 20- April- 2019].

[34]"About", *Sparesinmotion.com*. [Online]. Available: https://www.sparesinmotion.com/about. [Accessed: 3- May- 2019].

[35] C. Peeren, "REwind Willemsplein - Superuse Studios", *Superuse Studios*, 2012. [Online]. Available: https://www.superuse-studios.com/projects/rewind-willemsplein/. [Accessed: 23- May- 2019].

[36] J. Bergsma, "Wikado - Superuse Studios", *Superuse Studios*, 2007. [Online]. Available: https://www.superuse-studios.com/projects/wikado/. [Accessed: 10- May- 2019].

[37] B. Rahnama, "Reduction of Environmental Impact Effect of Disposing Wind Turbine Blades", *Diva-portal.se*, 2019. [Online]. Available: http://www.diva-portal.se/smash/get/diva2:691565/FULLTEXT01.pdf.

[38]"Recycling | WorldAutoSteel", *Worldautosteel.org*. [Online]. Available: https://www.worldautosteel.org/life-cycle-thinking/recycling/. [Accessed: 10- May- 2019].

[39] S. Karavida and R. Nõmmik, "Waste Management of End-of-Service Wind Turbines", *Projekter.aau.dk*, 2015. [Online]. Available: https://projekter.aau.dk/projekter/files/213319772/Waste_management_of_end_of_service_wind_turbines.pdf.

[40]"Steel solutions in the green economy Wind turbines", *Worldsteel.org*, 2012. [Online]. Available: https://www.worldsteel.org/en/dam/jcr:41f65ea2-7447-4489-8ba7-9c87e3975aab/Steel+solutions+in+the+green+economy:+Wind+turbines.pdf. [Accessed: 23- May- 2019].

[41] "Offshore support structures", *Wind-energy-the-facts.org*. [Online]. Available: https://www.wind-energy-the-facts.org/offshore-support-structures.html.

[42]"Industry joins forces to study the sustainable decommissioning of offshore wind turbine foundations - Deltares", *Deltares*, 2019. [Online]. Available: https://www.deltares.nl/en/news/industry-joins-forces-study-sustainable-decommissioning-offshore-wind-turbine-foundations/. [Accessed: 1- May- 2019].

[43]"Hydraulic Pile Extraction Scale Tests for testing the removal of piles from the soil at the end of their operational life | GROW Offshore Wind", *GROW Offshore Wind*, 2019. [Online]. Available: https://www.grow-offshorewind.nl/project/hype-st. [Accessed: 26- April- 2019].

[44] W. Leif and L. Jensen, "DECOMMISSIONING OF VINDEBY – THE WORLDS FIRST OFFSHORE WIND FARM", 2017.

[45] A. Gross, "Concrete chokes our landfill sites – but where else can it go?", *the Guardian*, 2019. [Online]. Available: https://www.theguardian.com/cities/2019/feb/26/concrete-chokes-our-landfill-sites-but-where-else-can-it-go. [Accessed: 23- April- 2019].

[46] S. Zafar, "Methods for Aluminium Recycling", *EcoMENA*, 2017. [Online]. Available: https://www.ecomena.org/recycling-aluminium/. [Accessed: 3- May- 2019].

[47] T. Russell, "Yttre Stengrund completely decommissioned", *4c Offshore*, 2019. [Online]. Available: https://www.4coffshore.com/windfarms/yttre-stengrund-completely-decommissioned-nid3199.html.

[48] J. Hill, "World's First Ever Offshore Wind Farm Finally Dismantled", *CleanTechnica.com*, 2017. [Online]. Available: https://cleantechnica.com/2017/09/11/worlds-first-ever-offshore-wind-farm-finally-dismantled/.

[49] L. Winther(Ørsted A/S), Interview through email, 2019

[50] R. Haworth, "Decommissioning of Utgrunden Complete", *4coffshore.com*, 2018. [Online]. Available: https://www.4coffshore.com/news/decommissioning-of-utgrunden-complete-nid8647.html?fbclid=IwAR2qxuhKVu5DiZQWYnYlwGZEfQZjCcr1rHrPTe6XmCcTd5i5D7ynZGyXYfI.[Accessed: 13- May- 2019].

[51] M. Jansson (Vattenfall AB), Phone interview, 2019

[52]"Nuon says bye to Lely", *renews.bis*, 2016. [Online]. Available: https://renews.biz/40655/nuon-says-bye-to-lely/. [Accessed: 14- May- 2019].

[53] T. Haugstad, "Har kuttet kostnadene på flytende havvind med 70 prosent", *tu.no*, 2017. [Online]. Available: https://www.tu.no/artikler/har-kuttet-kostnadene-pa-flytende-havvind-med-70-prosent/378227.[Accessed: 28-Apr- 2019].

[54] G. Benveniste, M. Lerch and M. De Prada, "Innovative Floating offshore wind energy WP2: Socio-economic evaluation of floating substructures."

[55] N. Shil and M. Parvez, *Life cycle costing: an alternative selection tool*. 2007.

[56] G. Smith and G. Lamont, "Decommissioning of Offshore Wind Installations - What we can learn", *Researchgate.net*, 2017. [Online]. Available: https://www.researchgate.net/publication/318340068_Decommissioning_of_Offshore_Wind_Installations_-_What_we_can_learn.

[57] "UKCS Decommissioning", *Ogauthority.co.uk*, 2018. [Online]. Available: https://www.ogauthority.co.uk/media/4999/decommissioning-a5-2018-pdf-version.pdf.

[58] DNV GL, "Assessment of Offshore Wind Farm Decommissioning Requirements", *Ontario Ministry of the Environment and Climate Change*, 2016.

[59] ICF, "Decommissioning Methodology and Cost Evaluation." Available: https://www.bsee.gov/sites/bsee.gov/files/tap-technical-assessment-program/738aa.pdf. [Accessed 12 May 2019].

[60] M. Weeks (RGL Services), Interview through email, 2019

[61] Removal of Met Mast Monopile, Offshore Denmark. RGL Services, 2019.

[62] Adoption of Novel Solutions Decommissioning in the North Sea. ARUP, 2015.

[63]"OSPAR Inventory of Offshore Installations - 2015", *Odim.OSPAR.org*, 2015. [Online]. Available: https://odims.ospar.org/documents/378. [Accessed: 23- Apr- 2019].

[64] R. Ramsdal, "Plattformer klare for å skrotes - dette er ryddejobben på norsk sokkel", *Tu.no*, 2019. [Online]. Available: https://www.tu.no/artikler/plattformer-klare-for-a-skrotes-dette-er-ryddejobben-pa-norsk-sokkel/364797.

[65] J. Thrane (AF Offshore Decom), phone interview, 2019.

[66]"News - Fred. Olsen Windcarrier", Fred. Olsen Windcarrier, 2019. [Online]. Available: https://windcarrier.com/media/news/.

[67] K. Madsen (Momentum Gruppen A/S, interview through email, 2019.

[68] WindEurope, "Driving Cost Reductions in Offshore Wind." Available: https://windeurope.org/wp-content/uploads/files/about-wind/reports/LEANWIND-Driving-cost-reductions-in-offshore.pdf?fbclid=IwAR0eDKRSxEcIvWI1EDzLgNPdNJFwzYNqKQ3zyTE7MtbOKH29luknGbsDXWQ.

[69] *Cost estimation and liabilities in decommissioning offshore wind installations*. ARUP, 2018.

[70] B. Bulder and M. Van Roerrmund, *Lifecycle and decommissioning offshore wind*. ECN, 2016.

[71] C. Richard, "GALLERY: 'First' offshore repowering completed GALLERY: 'First' offshore repowering completed", *Windpoweroffshore.com*, 2018. [Online]. Available: https://www.windpoweroffshore.com/article/1520172/gallery-first-offshore-repowering-completed.

[72] J. Gerdes, "World's First Offshore Wind Repowering Completed in Sweden", *Greentechmedia.com*, 2018. [Online]. Available: https://www.greentechmedia.com/articles/read/worlds-first-offshore-wind-repowering-completed-in-sweden#gs.dvf360. [Accessed: 10- May- 2019].

[73] L. Ziegler, E. Gonzalez, T. Rubert, U. Smolka and J. Melero, "Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK", *Sciencedirect.com*, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032117313503. [Accessed: 28- Apr- 2019].

[74] Megavind, "Strategy for Extending the Useful Lifetime of a Wind Turbine", 2016. Available: https://ens.dk/sites/ens.dk/files/Forskning_og_udvikling/strategy_for_extending_the_useful_lifetime_of_a_wind_turbine_2016.pdf.

[75] Siemens Gamesa, "Siemens Gamesa to extend the useful life of a customer's entire fleet of wind turbines in Aragon, Spain by 10 years until year 30", *SiemensGamesa.com*, 2018. [Online]. Available: https://www.siemensgamesa.com/en-int/newsroom/2018/11/contract-services-spain-aragon-wind-turbines. [Accessed: 2- May- 2019].

[76] B. Bedeschi, "Europe's new permit, grid rules set to hike wind repowering spending", *NewEnergyUpdate.com*, 2019. [Online]. Available: http://newenergyupdate.com/wind-energy-update/europes-new-permit-grid-rules-set-hike-wind-repowering-spending. [Accessed: 05- May- 2019].

# 8 List of Figures

# 9 List of Tables