CABLES DECOMMISSIONING IN OFFSHORE WIND FARMS:
ENVIRONMENTAL AND ECONOMICAL PERSPECTIVE

Dissertation in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE WITH A MAJOR IN WIND POWER
PROJECT MANAGEMENT

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Department of Earth Sciences, Campus Gotland

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ABSTRACT

Addressing the decommissioning issues is vital to ensure a sustainable and effective process of such an essential part of the project life cycle. While there is a set of good practice and regulations that govern most of the decommissioning activities, the cable decommissioning issue is still in a big debate and often left abandoned at the seabed due to environmental concerns, as justified by most developers. This paper is aiming to understand the environmental and economic consequences of cable decommissioning.

The available research papers and reports that are dealing with cable decommissioning issues have been reviewed. The cables are often decommissioned using similar methods to installation. However, there are no regulatory obligations to removing the cables in most countries. Cable installation will be associated with environmental impacts, but they are considered to be negligible. Additionally, Recycling cables’ copper is beneficial in both aspects environmentally and economically as copper prices are on the rise.

A comparison between the ESs and decommissioning programs in a number of OWFSs have been conducted to understand the justification used for abandoning the cables. Most of the decommissioning reports have considered cable decommissioning to cause “considerable damage to seabed ecology”. However, that contradicts what was found in the ESs, where the impact level was considered negligible and anticipated to be similar to installation. It was unclear whether the abandonment of cables was driven by environmental consideration or not.

A case study has been selected to compare cable and monopile decommissioning cost and the contribution of each component to the total decommissioning cost, including possible revenue generated from recycling. It was found that the cost-benefit of cable decommissioning is incomparable to monopile decommissioning as the latter is very costly, and the possible residual value is insignificant when compared to cables. Moreover, it is possible that the total cable decommissioning cost to be largely offset by the revenue generated from copper resell. Additionally, the cable decommissioning total cost can be almost paid by recycling cables if copper prices increase in the near future.

Keywords: Offshore wind energy, subsea cables, decommissioning
ACKNOWLEDGEMENTS

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Finally, my most profound appreciation to my family, especially my wife, for the support and patience they have shown since the beginning of this journey.
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<table>
<thead>
<tr>
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<tr>
<td>AC</td>
<td>Alternative Current</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>EIA</td>
<td>Environmental Impact Assessment</td>
</tr>
<tr>
<td>ES</td>
<td>Environmental Statement</td>
</tr>
<tr>
<td>kV</td>
<td>Kilovolt</td>
</tr>
<tr>
<td>OWF</td>
<td>Offshore Wind Farm</td>
</tr>
<tr>
<td>ROV</td>
<td>Remotely Operated Vehicle</td>
</tr>
<tr>
<td>WTG</td>
<td>Wind Turbine Generator</td>
</tr>
<tr>
<td>OSV</td>
<td>Offshore Service Vessel</td>
</tr>
<tr>
<td>SSOWF</td>
<td>Sheringham Shoal Offshore Wind Farm</td>
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CHAPTER 1. INTRODUCTION

The rising concerns about climate change and energy security have pushed many countries to look for an alternative energy source than conventional fossil fuel, with wind power technology proven to be a successful candidate. The exploitation of onshore sites has been pushed to the limits in recent years, making it necessary to explore new areas for wind turbine deployment resulting in ever-increasing attention to the offshore wind industry.

Since the first offshore wind farm was built in the early ’90s, the offshore wind industry has evolved dramatically to reach a level that can compete with other conventional energy sources. While the planning and constructions problems of offshore wind projects have been overcome, there is still a lack of knowledge regarding end-of-life strategies, especially with very few offshore wind farms that have been decommissioned (Eva Topham et al., 2019a). Today, there are around 116 offshore wind farms around European waters (Wind Europe, 2021); almost 30% of these offshore projects are older than 15 years (Eva Topham et al., 2019a). Given an operational lifetime of 20 years, the need to thoroughly prepare for decommissioning of these projects is urgent (Eva Topham et al., 2019a).

Moreover, the number of offshore wind farms to be decommissioned in the future will increase significantly in the coming years; as shown in Figure 1, the next decade will witness the decommissioning of more than 10 OWFs that are of significant size and capacity when compared to the already decommissioned OWFs. Additionally, the number, size and capacity, and distance to shore of the newly built OWFs have seen tremendous growth in the past few years. For instance, in 2020 and only in Europe, a new 356 OWFs totalling a 2.9 GW of capacity have been connected to the grid making Europe’s total offshore wind reaching a record-breaking capacity of 25 GW (Wind Europe, 2021). Furthermore, the average distance to shore has increased from only a few Km to around 52 Km in 2020, in addition to the increase in the average water depth from merely a few meters to 44 m (Wind Europe, 2021). Such an exponential increase in the number of OWFs and wind turbines offshore will be associated with an immense increase in the number of components that need to be disposed of when the operational lifetime of the wind farm ends, making it a necessity to address the decommissioning issues to ensure sustainable and safe growth of the renewable energy sector.

Decommissioning can be considered as the opposite of the installation, where the developer is to ensure that the site is recovered to its original state before the commencing of the project (Topham and McMillan, 2017). In offshore wind projects, decommissioning includes
removing all the wind turbines and their corresponding substructures. Most of the removed components are moved back to shore to be recycled or reused as spare parts (Topham and McMillan, 2017). However, the decommissioning procedures are more complex than just reversing the installation procedures. It depends on multiple factors, such as cost, environmental impact, and legislative framework that determine what is allowed or not during the decommissioning (Kerkvliet and Polatidis Sheringham Shoal, 2016).

Figure 1. number of offshore wind farms to be decommissioned per year (Source: Topham and McMillan, 2017)

1.1Problem Formulation

While there is an agreement on removing wind turbines and their foundations across the industry and legal entities, there is still a considerable debate on removing inter-array and export cables of offshore wind projects. The problem is manifested even more with the lack of a clear regulatory framework on what is required to be removed or left in situ and the lack of experience on the environmental impact of such a decision. According to most regulations, “full removal” should be the default in all projects. However, in reality some projects have left cables in situ; others are planning to do the same. Such a decision is often justified with environmental cases that describes leaving cables is actually better for the environment than
pulling them out. Such a dilemma is considered a burden to both developers and stakeholders when planning the decommissioning program, especially with no clear statement on the requirement to remove cables in most regulations.

1.2 OBJECTIVES AND RESEARCH AIM

Since there is this big debate, this research aims to shed some light on the environmental and economic aspects of cable decommissioning for offshore wind farms by investigating the cables environmental impacts in both cases of total and non-removal via analyzing the available literature and decommissioning programs of offshore wind farms. Secondly, perform a cost estimate to evaluate the economic consequences of complete cables removal compared to another subsea component decommissioning such as monopiles. Additionally, considerations have been taken to estimate the possible revenue from recycling the cables and the opportunity of offsetting the total decommissioning cost by doing so. Ultimately, the outcomes of this study will provide an insight to both developers and stakeholders for utilizing the decommission programs of future offshore wind farms.

1.3 OUTLINE

In this paper, Chapter 2 will provide a literature review on the regulations followed by most countries. The different cable decommissioning methods and the possible associated environmental impact are reviewed together with the publicly available models to evaluate decommissioning costs. In Chapter 3, the methodology followed in conducting this research is explained, whereby in Chapter 4, the methodology is applied, and the main outcomes are outlined. Chapter 5 will analyze and discuss the results of this study to be concluded in Chapter 6, together with suggestions for further research.
CHAPTER 2. LITERATURE REVIEW

Numerous researches have addressed the offshore wind power projects decommissioning as a whole, focusing mainly on wind turbine removal and its associated substructure. Multiple studies have reviewed the decommissioning regulations, environmental impact and cost modelling, yet very little attention was paid to cable decommissioning. This chapter will review the available literature related to offshore cable decommissioning regulations, removal methods and recyclability of cables, associated environmental impacts of cable removal or abandonment, and finally, the available decommissioning cost modelling that includes cable decommissioning cost.

2.1 Decommissioning standards and regulations

The responsibilities for decommissioning offshore energy installations are governed by international, national and regional laws and regulations. The United Nations Convention on the Law of the Sea (UNCLOS) is considered the primary international regulations, which transposed by the International Maritime Organisation (IMO). At the same time, in the North-East Atlantic, the Oslo and Paris (OSPAR) convention is also binding (Smith et al., 2016).

Two main basic principles drive these regulations. The first principle is that, ideally, all offshore installations and equipment should be removed entirely. However, some flexibility is provided based on if the total removal will be associated with extreme risk, cost, or adverse environmental damage. Some cases allow installation to be left in situ if they will serve a new purpose, such as artificial reefs. Regarding offshore wind installations, such conditions are applicable to piles, buried cables, and scour protection. To ensure that the developer will meet his decommissioning liability, the polluter pays principle is applied where the developer is required to make adequate provisions that cover their decommissioning liabilities. Such requirements are usually in the form of an irrecoverable bond or cash deposit provided prior to the commissioning of the project (Smith et al., 2016).

The UNCLOS convention grants coastal states the right to construct, authorize and regulate the construction, operation and use of offshore installations and structures in their exclusive economic zone (Yiallourides and Gordon, 2019). However, the convention is rather simplistic when it comes to decommissioning and contains only one article dealing with removing abandoned offshore installation leading to multiple interpretations (Yiallourides and Gordon, 2019). The article reads as follow:
Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent international organization. Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States. Appropriate publicity shall be given to the depth, position and dimensions of any installations or structures not entirely removed. (UN, 1994)

Later on, in 1998, the OSPAR convention adopted to regulate the decommissioning of offshore installations. The convention had a binding decision to ban the disposal of offshore installation into the sea unless there is a strong reason not to do so. The IMO convention consists of guidelines that provide general removal requirements and standards, but these guidelines are not necessarily legally binding (Yiallourides and Gordon, 2019). Moreover, the IMO guidelines suggest that offshore installation removal should be evaluated on a case by case basis by the relevant coastal states. (Yiallourides and Gordon, 2019). However, none of the conventions had a clear statement on whether the sub-sea cables need to be removed or not, but instead, it was left for the local authority to decide based on their contract with the wind farm owner.

Nonetheless, and despite no legal requirement for cable removal, the cable owner will continue to have perpetuity legal responsibility for the abandonment of cable as set by international laws (Burnett, 2004). Moreover, the owner liability for any environmental impact or effect on surface navigation or other sea uses will not be omitted as time progresses. In fact, the cable owner will have to indemnify the affected party for any damage to occur, such as the loss of anchor or fishing equipment if the cable will be uncovered in the future (Burnett, 2004).

One of the first authors that have addressed the need for a unified and integral decommission policy in Europe were Januário, Semino and Bell (2007). They have argued that the decommissioning of offshore wind farms is an important issue that should be considered and integrated within the European Maritime Policy, especially with the high ambition of EU members to exploit offshore wind resources. Therefore, the marine policy should be able to handle this expected growth. Moreover, the different country legislations and requirements may interfere with the broader marine environment and spatial planning. They have suggested that a unified EU maritime policy should be able to formulate the minimum standards required for the decommissioning of offshore wind projects to regulate and harmonize the sea users as
the industry seems not to pay much attention to decommissioning aside from including it in the permitting application. After reviewing several EU countries legislations, they have concluded that only a few countries have explicit offshore windfarms decommissioning procedures. Most of Europe’s regional seas are subject to UNCLOS, and they have derived their local legislations from the UNCLOS and the OSPAR convention.

Topham and McMillan (2019), throughout their paper “Challenges of decommissioning offshore wind farms: Overview of the European experience”, have shared the same concerns regarding renewable offshore industry regulations and guidelines also that they are inadequate and lack recommendations of best practice. Furthermore, they are mainly adopted from the oil and gas industry and often do not apply to renewable energy projects. Additionally, Topham and McMillan have stressed that the lack of prescriptive regulation on what needs to be removed can lead to non-sustainable decommissioning solutions, as decommissioning decisions will be made based only on economic drives. However, the cable decommissioning issue was not thoroughly analyzed in the paper as it was assumed that the cables would be left in situ in most cases.

Such generic international laws and conventions have led most countries to adopt a different approach with respect to offshore project dismantling. Aldén et al. (2014) have done extensive research in cooperation with the Swedish Energy Agency to identify the decommissioning regulations of multiple countries in Europe (Denmark, France, Germany, Spain, and the United Kingdom) in addition to the USA and pinpoint the difference between each other. The selection of the countries was based on their history of dealing with wind power project dismantling both onshore and offshore. Although the research focuses mainly on onshore projects dismantling, cost modelling, and security bond requirements, it has provided a good overview of the offshore project decommissioning regulations in the selected countries. For all the studied countries, the Environmental Impact Assessment (EIA) of the project should describe the dismantling process and how foundations and cables are going to be handled and will be assessed as part of the project application for the permit. The dismantling rules for offshore project in these countries are mainly examined to a high extend by national authorities, contrary to the land-based projects where local authorities are highly involved in the decision.

The paper concludes that most countries have clear regulations on removing wind turbine essential parts, such as foundations. Some countries have indicated the required depth where structures above should be removed. For instance, in France, the restoration level within the wind turbine area should be at least one meter below sea level, while in the USA, that depth
extends to 5 meters; other countries have not specified such requirement. However, the cable removal was not indicated to be obligatory to remove in all the reviewed countries, except for the USA, where it was clearly stated that seabed should be cleared and all the cables to be removed. In contrast, other countries have left that decision to be evaluated on a case by. The need for security bonds for all offshore projects is required in all the studied countries, yet the amount of such provisions was not specified due to the unknown cost of disassembly of offshore structures. Moreover, it was not specified whether the security bond should include the cable decommissioning cost in any case.

2.2 Cables Features, Removal Methods and Recyclability

The subsea cables for offshore wind farms consist of inter-array cables and export cables. The design of such cables is influenced by multiple factors such as connection voltage and capacity, turbine size, and distance from shore (BERR, 2009). The cables are designed to transmit electric current, either Alternating (AC) or Direct DC, with AC being the most frequently used in offshore renewable energy applications for being cheaper than DC alternative in close to shore projects (Taormina et al., 2018). The cable configuration can vary from being a monopolar, bipolar, or three-phase system with diameters ranging from 5 to 30 cm and weighing between 15 and 120 kg m\(^{-1}\) (Taormina et al., 2018).

To contain the emitted electric fields, cables usually are insulated with EPR (Ethylene Propylene Rubber) or XLPE (Cross-Linked Polyethylene). Some High voltage cables use oil as an isolating medium within the cable, but that is not widely applicable due to environmental risks associated with oil leakages (BERR, 2009). Almost all offshore wind farm projects use XLPE as an insulation material for the cables; even though EPR offers better water resistance and flexibility, it is not commonly used due to higher dielectric losses than the XLPE alternative (Smith et al., 2016). Due to the harsh offshore environment and to reduce the risk of cable damage from anchoring or fishing activities, specific armouring layers are also added to the cable in addition to burying them under the seabed. The burial depth can vary from one project to another, depending on the used method of installation and seafloor characteristics (Taormina et al., 2018).

The inner-array cables are used to connect the wind turbines into arrays and also connect the various arrays to transmit the produced power to the substation. The array cable length is usually short, ranging between 1 to 2 km depending on the spacing between the wind turbines,
which is usually 6 to 8 rotor diameter (Smith et al., 2016). The operating voltage for intermarrily cables is generally at 36 kV (BERR, 2009) with three copper or aluminium cores.

On the other hand, the export cable is used to transmit the power from the wind farm to the grid connection onshore. The length of the export cable can extend to several Km, depending on the distance to shore from the substation that can exceed 30 km or more. The most commonly used configuration is three core AC cable with operating voltage > 100 kV (Worzyk, 2009). However, with the current trend of offshore wind project being further offshore and having more capacity, the high voltage DC cables can provide a more economical solution than AC connection, especially with the transmission distance exceeding 60 Km (Zhan et al., 2010). Moreover, using multiple export cables instead of one is also a common practice used in offshore wind farms with multi-hundred Mw of capacity (Wood, 2020). Figure 2 summarizes the most commonly used submarine cables and their applications, where type 1 represents the inter-array cables, and type 2 is widely used as an export cable. The figure also contains a description for cables (type 3, 4, and 5) that are designed to transmit higher power for longer distances, which is believed to be applicable for big offshore wind projects with higher capacity and further away from shore.

<table>
<thead>
<tr>
<th>Type</th>
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<th>3</th>
<th>4</th>
<th>5</th>
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<tr>
<td>Rated Voltage</td>
<td>33 kV AC</td>
<td>150 kV AC</td>
<td>420 kV AC</td>
<td>320 kV DC</td>
<td>450 kV DC</td>
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<tr>
<td>Insulation</td>
<td>XLPE, EPR</td>
<td>XLPE</td>
<td>Oil/paper or XLPE</td>
<td>Extruded</td>
<td>Mass-impregnated</td>
</tr>
<tr>
<td>Typical Application</td>
<td>Supplying small islands, connection of offshore wind turbines</td>
<td>Connecting islands with large populations, offshore wind parks export cables</td>
<td>Crossing rivers/straights with large transmission capacity</td>
<td>Long distance connections of offshore platforms or wind farms</td>
<td>Long distance connection of autonomous power grids</td>
</tr>
<tr>
<td>Maximum Length</td>
<td>20–30 km</td>
<td>70–150 km</td>
<td>&lt;50 km</td>
<td>&gt;500 km</td>
<td>&gt;500 km</td>
</tr>
<tr>
<td>Typical Rating</td>
<td>30 MW</td>
<td>180 MW</td>
<td>700 MW/three cables</td>
<td>1000 MW/cable pair</td>
<td>600 MW/cable</td>
</tr>
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Figure 2 description of submarine power cable and their application (Source: Taormina et al., 2018)
**Removal Options**

The cables decommissioning have three options in general, namely complete removal of cables, partial removal of cables, or leave all in place (Ostachowicz et al., 2016).

In case of a non-removal option, the cables should be buried at an appropriate depth (1-3 m) to exclude any safety risks to the marine users and limit the environmental or pollution impacts (Topham and McMillan, 2017). If cables are buried in an area where the seabed sediments are mobile, the risk of cable being exposed is high and requires deeper burial (BERR, 2009). As the cable will be under the owner liability perpetuity, close monitoring is essential to ensure that cables do not become exposed under any circumstances; if so, the exposed parts need to be reburied again (Topham and McMillan, 2017). Although the term non-removal refers to the abandonment of cables in situ, it does not necessarily mean that any operations will not be performed in that regard. Such operations can include; removing sections where cables are crossing another operational cable, applying protective covers to cables ends to limit metal contaminations, and finally securely rebury any exposed part of the cables (Topham and McMillan, 2017).

The environmental impact of leaving cables in situ is yet unclear. To date, researchers have indicated that the total removal will cause substantial damage to the environment without further reasoning the impact of the other options (Topham and McMillan, 2017; Taormina et al., 2018; Eva Topham et al., 2019b). Nevertheless, cables are composed of heavy metals such as copper and lead that can potentially dissolve and contaminate the sediment if the cable shield is enacted. However, Taormina et al. (2018) argue that the dissolved quantities will not be considerable and have no significant impact.

As the name suggests, the total removal option would consider the de-bury of all the cables, retrieve them to the surface, and transport them to shore for recycling. Prior to any operation, surveys have to be conducted to assess the cable depth and removal method to be used, in addition to tools and equipment contracting (Smith et al., 2016). To de-bury the cables, similar techniques to installation will be used to uncover the cables from the seabed or by simply pulling them with enough force if the seabed consists of soft soil (Smith, Garrett and Gibberd, 2015). However, the process is not as simple as pulling cables, especially after many years, the seabed soil has consolidated around the cables. Hens, additional methods will have to be implemented to loosen the cables from the seabed. One of the methods is using “under-runs”, which consists of a device to be installed under the cables while being towed with a line from
a vessel (BERR, 2009). This method is only applicable to shallow burial depths (less than 1 m) and soft soils; therefore, it might not be adequate to be used in modern offshore wind farms where cables are buried in greater depths (BERR, 2009).

In case of deeper burial depth greater than 1 m, the use of jetting, ploughing or trenching tool method would be used to release the cable from the seabed. The selection of such techniques is highly dependent on the seabed conditions; it can be said that the cable removal will mostly follow similar procedures to the installation (Smith et al., 2016). The jetting and trenching tools are generally attached to a remotely operated vehicle dragged on the seabed by a vessel, as seen in Figure 3. The jetting tool uses high-pressure water jets to fluidize the soft seabed and release the cable. In contrast, the trenching tool consists of a cutting wheel attached with replaceable cutting rocks that, when rotating it, will penetrate the seabed, helping to release the cable (BERR, 2009). On the other side, the ploughs are considered passive tools and use a cutting edge to share the soil around the cable while being pulled by a host vessel (IHC, 2021).

![Figure 3 Trenching tool (source: BERR, 2009)](image-url)
However, the ploughs are preferable when possible as they can rebury the trench left behind cable when being pulled out and are less disturbing than jetting and trenching (Kraus and Carter, 2018). Suppose the seabed consists of very hard rock or mobile sediments. In that case, alternative methods are followed to protect the cable instead of burial, such as concrete mats (Figure 4) that are deployed over the cables or rock dumping (Smith et al., 2016). Therefore, different operations to remove such protective methods have to be performed before cables are retrieved, which is typically associated with higher cost and environmentally more damaging, mainly if reefs have formed on the concrete mattresses (Taormina et al., 2018).

Regardless of the de-burial method, the cable end will be attached to the retravel vessel where they are spooled onto a drum or cut into lengths using a hydraulic cutting tool on board the vessel if the cables are not planned to be used afterwards (Smith et al., 2016; Topham and McMillan, 2017). Therefore the cable decommissioning vessel need to be equipped with the necessary tools to lift, cut and stow the cable and operate the de-burial vehicle with the possibility to use the same cable installation vessel (Smith et al., 2016).
As for the partial removal option, similar techniques to the total removal will be used except for the fact that not all the cables will be removed. The partial removal can include removing either the array cables or export cable with the array cable removal only is the most frequently mentioned in most literature as a partial removal option (Taormina et al., 2018; Eva Topham et al., 2019b).

**Recyclability**

The end-of-life processes of cables follow the same hierarchy of waste management that applies to all materials. The priority is given to reuse the cables, and if not possible, then properly recycling the cables with landfill being the least possible option given the high-value metal content in the cables and the increasing restrictions on landfilling materials. Theoretically, it is possible to reuse the cables as they are designed to have operational life exceeding 40 years (Eva Topham et al., 2019b). Nevertheless, the retrieval methods used will very likely damage the cables, and therefore it is assumed that cables will be recycled if removed in most offshore wind projects (Smith et al., 2016).

Recycling the cables starts with separating the cable core from the outer protective layer. Multiple separation methods have developed over the years; stripping technology is the most appropriate for large diameters cables (Li et al., 2017). An alternative method can be used by crushing the cable into small pieces while removing the steel that is part of the outer protective layer using magnets. The steam of metal/polymer will be further reduced in size and be fully separated at the end (Hagström et al., 2006). The metal components of the subsea cables are composed mainly of copper and aluminium. The technology of recycling such component is already established and efficient that can achieve purity of 99.5% after recycling (Karavida and Nõmmik, 2015).

Moreover, copper and aluminium can be recycled endlessly without losing their properties. The benefits of recycling such metals are well documented, especially for aluminium as one of the most energy-intensive to be produced from raw material (Jensen, 2019). Furthermore, the European copper institution (2020) consider copper recycling an efficient way to reintroduce valuable materials into the economy. Additionally, as recycling copper requires 85% less energy than producing it from raw material, the process will help cut 40 million tons of CO2 emissions annually.

One problematic area of recycling subsea cables is polymer insulation. While the primary motivation for recycling the cables is the value of the recovered metal, the disposal or recycling
of cable polymers have no economic benefits but rather related to waste management regulations. If the cable insulation is composed of EPR, it is relatively easy to recycle as it can be remelted into new products. Conversely, the XLPE polymers are much harder to recycle and usually end up being incinerated or landfill (Karavida and Nõmmik, 2015).

As indicated earlier, the main driver for retrieving the subsea cables (apart from the associated cost of the removal operations) is the copper content that has a high scrap value. Therefore, it is crucial to analyze the history of copper prices and future projects as it can have an impact on the final decision of cable decommissioning and, consequently, the entire decommissioning cost.

Since copper is a commodity, it is traded on the global market, where the price is governed by the offer and demand, making it less predictable. It can be seen in Figure 5, the historical trend of copper prices is very fluctuating, yet it has reached a historical value of 10,000 $/t in 2021 due to rising demand. It can also be seen in the figure how the prices are affected by the global market as by mid-2020, the prices dropped significantly due to the Covid-19 pandemic.

Such fluctuations can have an impact on the final decision of cable decommissioning as the metal prices are unknown by the actual removal of the cables, especially when the decommissioning program is designed in the planning phase 20-25 years earlier than the actual decommissioning. However, Bank of America expects that copper prices will continue to increase to reach double their value by 2024 and reach 20,000 $/t (Business insider, 2021b). This historical acceleration is believed to be driven by the growing industrial sector, especially as copper plays a crucial role in the electrification of the economy.

2.1 Environmental Impact of Cable Removal

To date, there is no dedicated published research that addresses the environmental impact of cable decommissioning that has been conducted on an OWF. The reason for that is the limited number of such projects and their proximity to shore. However, similar technics to cable installation will be used to remove them and, therefore, may generate a similar environmental effect (Smith et al., 2016; Taormina et al., 2018). Therefore, a review of the environmental impact of cable installation can provide an insight into what might be the effect during cable decommissioning.
Taormina et al. (2018) have researched to evaluate the environmental impact of submarine cables on marine ecology. The potential environmental effect that may arise from cable installation and decommissioning can include sediments resuspension, physical disturbance to benthic habitats, chemical pollutions, and underwater noise emissions. The sediments resuspension effect is highly dependent on the nature of the seabed and hydrodynamic conditions. Any operations on the seabed can lead to turbidity that can extend to several tens of hectares and will typically continue from few hours to few days. Suspended sediments can temporarily impact the efficiency of invertebrate filter-feeding fauna or bury the eggs of bottom laying species.

Moreover, a decrease in water transparency may also occur due to the resuspension of sediments, and that can impact the ability of fish to detect their prey visually. Nevertheless, the resuspension of sediments can generally have negligible impacts on marine ecosystems, as Taormina et al. concluded. A similar conclusion concerning suspended sediments has been found when reviewing a report released by the Department for Business, Enterprise and Regulatory Reform in the UK (BERR, 2009) that was dedicated to studying the different cabling techniques in the OWFs and the potential environmental impact of such activities.

The physical disturbance to the seabed is mainly created by equipment operating at the bottom, such as plough, trenching or jetting machines. Using such equipment may lead to direct
destruction of benthic habitats, such as displacement, damage and crushing of organisms. Yet, such effects are usually of small footprint depending on the method used. Worth noting that, ploughing method can cause less disturbances and faster recovery to seabed than any other cable operations equipment. However, regardless of the method used, the physical destruction and impact of any cable operations on the soft bottoms creatures can be considered of no significance and will not impact the biodiversity or abundance of the biomass along the cable route (Taormina et al., 2018).

Kraus and Carter (2018) have studied the physical seabed recovery following a protective burial of subsea cables in several locations around the globe. Kraus and Carter agree with Taormina et al. that the recovery rate from ploughing activities is faster than the rate of recovery from using water-jetted trenching. Moreover, the latter found to be more disturbing to seabed than ploughing. The seabed can recover to its original physical conditions at most in 2 years if ploughed, whereas it can be more than five years if trenched depending on the sediment supply rate at the location. The conducted surveys in the study suggest that the recovery rate of the biomass within the location is similar to the physical restoration mentioned earlier. Finally, the researchers have concluded that the disturbances associated with any cable burial activities have little impact on the benthos communities.

The potential chemical pollution risk from submarine cable operations can be seen as the release of heavy metals that are contained within the cables or hydrocarbons from vessels or oil insulated cables. Such pollution is considered rare as oil insulated cable has no longer been used since the 1990s, the possibility of heavy metal being dissolved is not likely to occur, and if so, it has no significant impact due to very low concentration (Taormina et al., 2018).

The underwater noise produced during the cable decommissioning operation can be generated from underwater equipments, such as plough or ROVs, and from the vessels that operate the equipment. The propagation and intensity of the generated noise can vary depending on the bathymetry and seabed characteristics. According to studies conducted on a cable installation for offshore wind farms, the maximum noise emission generated from ploughing or trenching can range between 178- 188.5 dB at 1 m from the operation area, according to studies conducted on a cable installation for offshore wind farms (Taormina et al., 2018). However, there is no documented evidence that underwater noise from subsea cable operations would affect marine animals or other marine life as such operations are localized and temporary.
2.2 Decommissioning Cost Models

There are numerous publications that are dealing with offshore wind farms decommissioning cost as a whole either by estimating the whole cost per Mw or estimating the cost by component. However, only a limited number of publications have counted for the total removal of subsea cables in their models and provided a methodology on how to estimate that.

One of the most recognized publication is the one by Kaiser and Snyder (2012), where they have provided a model to estimate the decommissioning cost of the different OWFs components, such as turbines, foundations, cables, and substation. The model to estimate the foundation removal cost provided two options based on the vessel strategy used, namely the single vessel model and the Offshore Support Vessel “OSV” model. In the single vessel option, a jack-up vessel or self-propelled installation vessel is used to support the cutting operations and place the foundation on a barge and shipped to port once the barge is full. The second option suggests using an OSV to support the cutting operation, and a lifting vessel will arrive only after the foundation is cut, thus reducing the total amount of time a larger vessel is needed. However, the latter option might be less expensive but requires the monopile to be held by the buried section by at least 4.5 m until the lifting vessel arrives, which is not a common practice when cutting the monopiles.

Kaiser and Snyder have also provided a methodology to estimate the cable decommissioning cost with the assumption that a low-cost vessel is used to remove the cables as the requirements are less severe than for the cable installation; moreover, it was also assumed that the cables would be cut in small sections instead of using the turntable to store them. The model provides cost estimation for both export cable and inner-array cables based on the time required to remove the cables times the vessel daily rate. The time to remove the cables was estimated from known installation rates with one distinction that the time to remove the cables is faster than the installation. It was assumed that the inter-array cables removal rate is twice as faster as the installation rate (0.3 km/d), while the export cable is 1.25 faster than the installation rate (0.7 km/day). Kaiser and Snyder model can be considered one of the first models that have accounted for the cable decommissioning and provided a detailed approach for that.

Topham and McMillan (2017), in their paper “Sustainable decommissioning of an offshore wind farm”, have provided a decommissioning cost estimation per Mw for a number of offshore wind farms in the UK based on their decommissioning program. The taken approach has also considered multiple alternatives decommissioning strategy to estimate the required
time and cost for decommissioning the studied OWFs. Based on the research results, the foundation removal cost was nearly half of the total decommissioning cost. Moreover, the decommissioning cost has varied significantly from one case to another due to the uncertainties when designing the decommissioning program and the site-specific conditions. However, the research did not consider cable decommissioning as it was assumed to involve high costs and environmental impact. Later on, Topham and McMillan (2019) have published another research focusing on recycling offshore wind farms and the possible cost reduction that can be achieved by doing so. The taken approach have considered recycling all the metals that can be found in the turbines and foundation. It was found that nearly 20% of the decommissioning cost can be paid by recycling the wind turbines and foundations. Nevertheless, the revenue from cable decommissioning was not considered and how much cost reduction can be achieved if all the copper in cables is recycled.

Finally, a review of a publication by Adedipe and Shafiee (2021) have been conducted. This publication can be considered one of the most recent public paper that has taken a detailed approach in estimating the OWFs decommissioning. Unlike the other models proposed to roughly estimate the cost associated with decommissioning the different components and trying to identify the cost driver behind each component, their suggested model has incorporated all the possible cost parameters associated with the different decommissioning phases using a cost breakdown structure approach. The research divides the decommissioning into four main phases: planning and regulatory, execution, logistics and waste management, and post decommissioning and within each phase, several underlining costs are calculated individually.

The cost of cable and foundation decommissioning is presented within the cost of execution, where it is summed up with other costs such as the preparation to remove the turbine and the cost of lifting and transportation. Adedipe and Shafiee model for cable decommissioning does not differ in principle from Kaiser and Snyder model, except it breaks down the cost into a more detailed approach. The cable decommissioning cost is estimated by multiplying the vessel daily rate and the time required to remove the cable, and the number of vessels used. Additionally, the number of trips required together with the daily rate for the transportation vessel and the required time to and from the shore. Moreover, the model breakdown the cost further to account for the number of personnel, personnel cost per day, and equipment per day.

Furthermore, the model provides a methodology to estimate the cost of logistics and waste management for the different wind farm components, as well as taking into account the most
common alternatives of the decommissioning strategies. The model can provide fewer uncertainties compared to other existing models as it gives the chance to calculate most of the cost associated with waste management, including onshore transportation and landfill tax. The reader can be referred to the aforementioned paper for further details with regard to the decommissioning of other offshore components.

Adedipe and Shafiee tested their model on a hypothetical 500 Mw offshore wind farm. When applying the model, the results have shown that the top three contributors to the decommissioning cost are the turbine and foundation removal, planning and regulatory cost, and the logistics cost having a share of 62%, 18% and 17%, respectively, whereas the cable decommissioning cost has represented only 1% of the total cost. The waste management activities were estimated to reduce the total cost by 4% with the assumption that only 60% of the removed structure weight is recycled. Woththnoting that only the inner-array cables were assumed to be decommissioned in the case study. Moreover, the scrap value was assumed to be constant (205.4 £/tonne) for all the recovered materials, which is far less than the actual value for copper scrap. Therefore, the cost reduction percentage from waste management cannot be representative if cables are decommissioned as no accurate estimate of the amount of recovered copper was provided.
CHAPTER 3. METHODOLOGY AND DATA

This chapter will present the methodology followed to establish this research. As outlined earlier, the purpose of this study is to understand the drive behind the decision of cable decommissioning in offshore wind projects. Multiple factors are often affecting the final decommissioning program, but they are mainly driven by environmental and economic considerations. Therefore, this thesis will consist of two main parts, namely, environmental analysis and cost-benefit analysis.

3.1 Environmental Analysis

Leaving cables in situ is often justified with environmental cases that describe cable decommissioning as an environmentally unhealthy practice. To analyze such claims, a thorough study of the available research papers on cable decommissioning removal methods, environmental impacts, regulations, and recyclability were conducted to evaluate the environmental impact of cable removal independently from what is justified in the decommissioning programs. Subsequently, a thorough review was performed on a number of publicly available decommissioning programs and EIA reports of existing offshore wind farms.

As most literature has indicated that similar technics to cable installation will be used to remove the cables, it is anticipated that a similar environmental impact to cable installation will arise from cable removal activities. Therefore, it was decided to compare the environmental impact of cable installation as stated in the studied EIA reports and compare that to the justification used in the decommissioning programs with regard to the planned cable removal options.

The selection of the decommissioning programs was based on their availability. Efforts were made to obtain decommissioning programs and post decommissioning reports for the very few decommissioned OWFs throughout contacting the relevant developers, but unfortunately, it was not possible to obtain such information as they were considered commercially sensitive. Therefore, all the analyzed decommissioning programs are for either operational wind farms that have not been decommissioned yet or under construction. A description of the selected OWF is outlined in Table 1.
Table 1 Summary table of the studied OWF

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Commission Year</th>
<th>Capacity (Mw)</th>
<th>Distance (km)</th>
<th>Total Cables length (km)</th>
<th>Burial depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sheringham Shoal</td>
<td>2012</td>
<td>316.8</td>
<td>17-23</td>
<td>126</td>
<td>1</td>
</tr>
<tr>
<td>2 Ormonde</td>
<td>2012</td>
<td>150</td>
<td>9.5</td>
<td>30</td>
<td>0.6-2</td>
</tr>
<tr>
<td>3 Greater Gabbard</td>
<td>2013</td>
<td>504</td>
<td>26</td>
<td>353</td>
<td>1-1.5</td>
</tr>
<tr>
<td>4 Gunfleet sands 2</td>
<td>2010</td>
<td>172</td>
<td>7</td>
<td>45.3</td>
<td>2</td>
</tr>
<tr>
<td>5 Dogger Bank A and B</td>
<td>Under construction</td>
<td>2x1200</td>
<td>131</td>
<td>705, 705</td>
<td>-</td>
</tr>
<tr>
<td>6 Lincs</td>
<td>2012</td>
<td>270</td>
<td>8</td>
<td>181</td>
<td>1-3</td>
</tr>
</tbody>
</table>

3.2 Cost-Benefit Analysis

To further understand the impact of cable decommissioning on the total cost and whether it is subjective to consider that “the total removal of covered cables will involve extreme costs”, a case study on an existing wind farm will be performed. The cost of cable decommissioning will be compared with the cost of decommissioning other subsea components, mainly foundations. Such comparison was chosen to test the contribution of the subsea component removal to the total decommissioning cost and whether the cable decommissioning will oppose a significant cost compared to foundation removal.

Sheringham Offshore Wind Farm (SSOWF) in the UK was selected for the case study in this research; the selection was based on the availability of sufficient information for the public. According to the decommissioning program, it was decided to leave all cables in situ, but for the purpose of this study, it will be assumed that all cables will be removed. The wind farm consists of 88 SWT-3.6-107 WTGs with a total capacity of 316.8 Mw. The wind farm is located approximately 17 km to 23km offshore from the coastal town of Sheringham on the north Norfolk coast in a water depth of 17-23 meters with a distance to the closest operational port around 40 Km (Peel Port). The foundations for wind turbines are monopiles with a diameter of 4.7 - 5.2 m and driven around 30 meters into the seabed. The inter-array (36 kV) cables consist of two types (Type 1 OD 132mm, Type 2 OD 105mm) with a total length of 82 km, while the export cable consists of two 145 kV copper cable 22 km each.
As for the economic consequences of cable decommissioning, they are barely touched upon in comparison to the decommissioning of other subsea components of the wind farms, mainly due to the very limited number of offshore wind farms that have been decommissioned; and the commercial sensitivity of such information that has not been made publicly available. Therefore, state of the art economic models for OWF decommissioning was reviewed to extract the potential costs of subsea components removal and the revenue from recycling.

A review of the scrap metal values was conducted to estimate the residual value from cables and foundations. Based on the prediction reviewed earlier, copper prices are expected to increase. Therefore, two scenarios will be considered to estimate residual value from cable recycling. The first scenario will consider the current prices of copper scrap that is around 4900 €/t for copper Bare Bright (Scrapmonster, 2021). The second scenario will assume an increase in scrap value based on the commodity prices. Usually, that should mean double the current scrap value, but a worst-case scenario will be considered assuming the scrap value to increase by 1.5 only, resulting in a future value of 7350 €/t. The steel scrap value will be considered constant at 140 €/t (Scrapmonster, 2021).

The cost of removing cables can be estimated by multiplying the time requires to remove the cables times the total daily rate for the vessel. The daily rate to remove the cables was estimated by Kaiser and Snyder (2012) to be 0.6 km/d for inner array cables and 0.9 km/d for export cable. Based on that, the total time to remove the cables can be calculated (cable length/removal rate). It will be assumed that a cable-laying vessel will be used to remove both export and inter-array cables, and it has a capacity of carousels up to 7000 tonnes (Prysmian Group, 2020). The vessel daily rate varies considerably through different reports; it ranges between 36,000- 100,000 €/day (Kaiser and Snyder, 2012; BVG, 2019; Adedipe and Shafiee, 2021), including all the associated cost of workers and equipment. Therefore, the average vessel daily rate will be taken to calculate the cost of removing the cables.

Due to the time limitation, it was not possible to perform a complete cost estimation to foundation removal for the selected case study, but instead, figures were sourced from Kaiser and Snyder (2012). In their study, they have estimated the cost of removal per foundation to be around 287,000 € for a monopile of 5.1 m in diameter using a single-vessel strategy. This estimation can be considered applicable to the selected case study as the average monopile diameter for SSOWF is 4.95 m; therefore, reliable estimates can be achieved.

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1 Currencies in this study have been adjusted to € based on the daily rate at the time of writing.
The total cost of decommissioning SSOWF was estimated by Topham and McMillan (2017) to be approximately 290,000 €/Mw. However, in Topham and McMillan paper, all cables are assumed to be left in situ, which did not allow to test cable removal contribution to the total decommissioning cost; therefore, the calculated cable removal cost will be added to the total cost.

The residual value will be calculated by multiplying the retrievable amount of material in tonne by the scrap value. The export cable consists of a 3x630 mm² copper core, while the inter-array cables are of a 3x400/3x185 mm² copper core. The exact length of each cable type is unknown; therefore, it will be assumed that each type will compose half of the total inter-array cables. The retrievable amount of steel from monopiles will be the average water depth plus 1 m below the mud line (as planned in the decommissioning program) multiplied by 9.97 t/m (Negro et al., 2017) to estimate the recoverable amount of steel. Table 2 below summarizes all the inputs to be used in the calculations.

Table 2 Summary of data used in the cost-benefit analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average water depth</td>
<td>20 m</td>
</tr>
<tr>
<td>inter-array cable core cross-section</td>
<td>3x400/3x185 mm²</td>
</tr>
<tr>
<td>inter-array cables total length</td>
<td>82 km</td>
</tr>
<tr>
<td>Export cable core cross-section</td>
<td>3x630 mm²</td>
</tr>
<tr>
<td>Export cable total length</td>
<td>2 x 22 km</td>
</tr>
<tr>
<td>Total cables weight</td>
<td>5147 t</td>
</tr>
<tr>
<td>Copper scrap value</td>
<td>4900-7350 €/t</td>
</tr>
<tr>
<td>Steel scrap value</td>
<td>140 €/t</td>
</tr>
<tr>
<td>Cable removal rate</td>
<td>0.6-0.9 km/d</td>
</tr>
<tr>
<td>Vessel daily rate</td>
<td>68,000 €</td>
</tr>
<tr>
<td>Cost of foundation removal</td>
<td>287,000 €/foundation</td>
</tr>
<tr>
<td>Total wind farm decommissioning cost</td>
<td>290,000 €/Mw</td>
</tr>
</tbody>
</table>
CHAPTER 4. APPLICATION OF THE METHODOLOGY AND RESULTS

Chapter 4 will present the results obtained from applying the outlined methodology. Section one of this chapter will illustrate the results from the environmental analysis, while section two will depict the main findings from the cost-benefit analysis.

4.1 Environmental Analysis Results

The results from analyzing the ESs for Sheringham Shoal (Scira Offshore Energy, 2006), Dogger Bank (Forewind, 2014), Greater Gabbard (2005), Gunfleet sands 2 (DONG Energy, 2007), and Lincs (Centrica, 2010a) offshore wind farms have shown that the increase of sediment concentration and disturbance to benthic ecology were the main concerns with regard to cable installation. It was also anticipated that the same effect would occur during cable decommissioning as stated in the ESs. Regardless of the impact criteria or the likelihood of the impact, the impact level on all aspects was considered to be negligible in all the analyzed ESs, as summarized in Table 3. Worth noting that all the cable installation methods were considered in the ESs, including water jetting and trenching and they were considered to be the worst-case scenario.

Table 3 Summary of the impacts associated with cable installation as analyzed from ESs

<table>
<thead>
<tr>
<th>Impact Criteria</th>
<th>During cable installation</th>
<th>Impact level</th>
<th>During cable decommissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re-suspension of seabed sediment</td>
<td>Likely to occur</td>
<td>negligible</td>
<td>Similar to installation</td>
</tr>
<tr>
<td>Increases in sediment concentrations</td>
<td>Likely to occur</td>
<td>negligible</td>
<td>Similar to installation</td>
</tr>
<tr>
<td>Disturbances to benthic infauna and epifauna</td>
<td>Direct impact, likely to occur</td>
<td>negligible</td>
<td>Similar to installation</td>
</tr>
<tr>
<td>Habitat loss</td>
<td>Possible destruction of spawning grounds</td>
<td>negligible</td>
<td>Similar to installation</td>
</tr>
<tr>
<td>Natural fish resource</td>
<td>Potential impact, habitat loss</td>
<td>negligible</td>
<td>Similar to installation</td>
</tr>
<tr>
<td>Noise and vibration</td>
<td>Indirect impact</td>
<td>negligible</td>
<td>Similar to installation</td>
</tr>
</tbody>
</table>
All the studies offshore wind farms have planned to leave all cables in situ except small sections; if there is cable crossing at any point, these sections will be cut and removed. The main justification in the decommissioning programs for leaving cables in situ was found to be “considerable damage” to seabed ecology and increase of suspended sediments, as summarized in Table 4.

Table 4 Summary of the results from Studying the decommissioning programs

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Decommissioning plan</th>
<th>Cable installation Impact from EIA</th>
<th>Leaving cables Justifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sheringham Shoal (Scira Offshore Energy, 2014)</td>
<td>Leave all in situ</td>
<td>Negligible impact on all aspects</td>
<td>Considerable damage to seabed ecology</td>
</tr>
<tr>
<td>2 Ormonde (Transmission Capital, 2012)</td>
<td>Leave all in situ</td>
<td>Negligible impact on all aspects</td>
<td>Considerable damage to seabed ecology</td>
</tr>
<tr>
<td>3 Greater Gabbard (GGOWs, 2007)</td>
<td>Leave all in situ</td>
<td>Negligible impact on all aspects</td>
<td>Considerable damage to seabed ecology</td>
</tr>
<tr>
<td>4 Gunfleet sands 2 (Dong Energy, 2012)</td>
<td>Leave all in situ</td>
<td>Negligible impact on all aspects</td>
<td>Not Justified</td>
</tr>
<tr>
<td>5 Dogger Bank A and B (Dogger Bank Windfarms, 2020)</td>
<td>Leave all in situ</td>
<td>Negligible impact on all aspects</td>
<td>Disturbance to the seabed</td>
</tr>
<tr>
<td>6 Lincs (Centrica, 2010b)</td>
<td>Leave all in situ</td>
<td>Negligible impact on all aspects</td>
<td>Not Justified</td>
</tr>
</tbody>
</table>

4.2 Cost-Benefit Analysis Results

Table 5 presents a cost breakdown of removing each component together with the possible revenue from recycling based on the figures presented in the methodology. The calculations were performed taking into account the future values of copper prices to estimate possible revenue generated from scrap resell. On the other hand, Figure 6 illustrate the impact of removing each component on the total wind farm decommissioning cost besides the possible cost reduction from reselling scrap.
Table 5 Estimated cost for cable and monopile decommissioning with the possible residual value.

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Export cable</th>
<th>Inter array cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to remove cables (day)</td>
<td>49</td>
<td>137</td>
</tr>
<tr>
<td>Cable removal cost (€)</td>
<td>3.3 M</td>
<td>9.3 M</td>
</tr>
<tr>
<td>Recovered copper from cables (t)</td>
<td>744</td>
<td>647</td>
</tr>
<tr>
<td>Revenue from copper resell (€) (current scrap value)</td>
<td>3.6 M</td>
<td>3.1 M</td>
</tr>
<tr>
<td>Revenue from copper resell (€) (Future scrap value)</td>
<td>5.4 M</td>
<td>4.7 M</td>
</tr>
<tr>
<td>Total cable decommissioning cost (€)</td>
<td>12.6 M</td>
<td></td>
</tr>
<tr>
<td>Total revenue from copper resell (€)</td>
<td>6.8 - 10.2 M</td>
<td></td>
</tr>
<tr>
<td>Monopile decommissioning Cost (€)</td>
<td>25.2 M</td>
<td></td>
</tr>
<tr>
<td>Recovered steel from monopiles (t)</td>
<td>18,424</td>
<td></td>
</tr>
<tr>
<td>Revenue from steel resell (€)</td>
<td>2.5 M</td>
<td></td>
</tr>
<tr>
<td>Total wind farm decommissioning cost (€)</td>
<td>104.5 M</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6 Contribution of the different subsea component decommissioning to the total decommissioning cost by percentage
CHAPTER 5. DISCUSSION AND ANALYSIS

This chapter will discuss the results presented in chapter 4 and analyze the environmental and economic impact of cable decommissioning compared to cable installation and other subsea components.

5.1 Results from the environmental analysis

In Table 3 it can be observed that all the analyzed ESs have agreed that the environmental impact of cable decommissioning is anticipated to be similar to the environmental impact of cable installation. The ESs have studied all the possible impacts that will arise from cable installation, including the increase of sediment concentration and destruction to benthic ecology. Moreover, the ESs have considered the different types of seabed lithology.

It was found that seabed consists of chalk are prone to have more impact when trenched compared to other seabed lithologies as there will be a release of more fine sediments that are likely to remain suspended indefinitely, according to the ESs. Such impacts are concluded to be direct and likely to occur, yet the impact level was considered to be negligible regardless of the seabed lithology or the technology used for cable burial since it would be temporary and of a small footprint. Moreover, all the reviewed literature has agreed that cable installation has no significant impact on the environment, and any trenches left behind would take at most 2-5 years to full physical recovery.

However, despite the clear statement that the impact level during the decommissioning phase will be similar to the construction phase, it contradicts the justification used in a number of the decommissioning programs and some literature to leave the cables buried into seabed. Sheringham Shoal, Ormonde, Greater Gabbard, and Dogger bank OWFs have stated in their decommissioning program that “considerable damage to seabed ecology” would occur if cables are to be removed.

Moreover, in Sheringham Shoal and Greater Gabbard decommissioning programs, the considerable length of cables and the need for jetting techniques were added as justification for not removing the cables, yet that was not the case when installing the cables as described in the ES. As for the other studied OWFs decommissioning reports, it was not justified clearly the reason behind abandoning cables but instead, it was noted as no regulatory obligations to removing such components in the decommissioning program description.
If the decision of decommissioning cables to be taken from a purely environmental perspective, then removing cables cannot be considered an environmentally unhealthy practice. In fact, removing other subsea components of the wind farm, such as monopiles, is considered to cause environmental damage since such structures serve as artificial reefs, yet they are removed due to regulatory obligations. By the same token, recycling copper from cables, as the European copper institute stated, would save energy and CO2 emissions by 85% and impact positively on the circular economy principle, thus contributing to the sustainability goals adopted by the wind farms developers.

Subsequently, the reviewed decommissioning programs are the ones that are used to consult with the different stakeholders, and based on the information provided by the developer, the stakeholders give their consent or rejection to the final plan. If such limited information is provided to the stakeholder, the outcomes of the decisions might not be relevant to the actual case. Moreover, some of the stakeholders have expressed their concerns when responding to the decommissioning program of Sheringham Shoal wind farm and have preferred that the cables be removed. However, the developer either responded that the cables would be buried under sufficient depth or refired to OSPAR guidelines for cables and pipelines as a notion for no regulatory obligation to remove the cables.

It can be said from reviewing the literature, ESs, and the decommissioning programs that the cable removal cannot oppose any significant impact and should not be taken as the sole justification for not removing the cables. However, it cannot also be generalized that cable decommissioning does not have an adverse impact on the environment, as this has to be evaluated case by case depending on the seabed conditions and the existing ecology on site. Although what can be said is that cable decommissioning, most likely, will have a similar environmental impact to cable installation as similar technics are used in both operations.

5.2 Cost-benefit analysis results

The results from the cost-benefit analysis listed in Table 5 have shown that monopile decommissioning would cost 25 million € and contribute by 24% to the total decommissioning cost for the selected case study. When compared to the cable decommissioning cost, cable removal would make up only 12% of the total cost, as illustrated in Figure 6. It is evident that cable decommissioning cost would be much less than the monopile decommissioning cost, making the statement that “cable removal would involve extreme costs” questionable.
If we consider the revenues generated from metal resell, steel from monopiles will help reduce the cost only by 2%. On the other hand, revenues from copper would achieve cost reduction by 7% with the current scrap value. Given the decommissioning of the case study would occur in the future, and based on the increase in copper prices, the residual value from cable decommissioning would help reduce the total cost by 10%. It is unclear whether such prediction is likely to occur or not, but even with the current scrap prices, the copper from cables would help offset the total decommissioning cost to a larger extend than steel from monopiles.

From a cost-benefit perspective, it is pretty apparent that monopile decommissioning cost cannot be offset by the revenues from steel resell by all means as it is, in essence, a highly complex process that requires costly equipment and experienced personnel. Even if cost reduction to be achieved in the future, the steel scrap value is not likely to increase and reach a level that can help offset the monopile decommissioning further than it is nowadays.

Contrarily, the residual value from copper can offset the total cable decommissioning cost considerably. Even with the current prices, the profit from copper pays back more than half of the cable removal cost. If the copper prices increase, almost all the cable decommissioning cost can be paid back from copper recycling. Consequently, the benefit of removing the cables is impacting positively on the cost when weighing it against the cost-benefit of removing the monopiles.

However, the presented results are merely a rough estimate based on the publicly available data, which, as have pointed out earlier, varied significantly throughout the different sources. For instance, the vessel daily rate taken from sources (which are also based on estimates) includes all the cost of personnel and equipment, yet that can vary depending on the technology adopted, availability of such vessels, and the type of contract of hiring such vessels and thus, there are uncertainties with the cable decommissioning cost. Nonetheless, it is believed that the presented cost of cable decommissioning is pessimistic. Given the continued development of the offshore wind industry and the trend of cost reduction on all aspects, including logistics, the actual cost of cable decommissioning can be lower in the future.

Moreover, the waste management cost was not taken into consideration in this study, and that can impact the revenue generated from recycling. However, the impact cannot be of significance as; 1) the revenue was calculated based on the net copper weight eliminating the polymer and armouring weight, 2) the presented scrap value is, in most cases, means that the buyer will bear all the associated cost of recycling, 3) if we to consider that the polymer and
armouring to be landfill, the landfill tax (in the UK for instance) are insignificant compared to the cost and revenue generated. Therefore, the revenue generated from metal resell can be considered representative of the studied case.

Another area of uncertainties may lie within the total decommissioning cost and the monopile removal cost. The total decommissioning cost sourced from Eva Topham study (2017) did not count for the planning and regulatory cost, a detailed approach for the logistics cost, and it was mainly focused to show the turbine and foundation removal impact on the total decommissioning cost. Therefore, it is anticipated that the actual decommissioning cost of the case study might be higher than what has been presented, and that can impact the actual contribution of all the presented results. However, the aim of this research is to show that cable decommissioning does not involve excessive costs compared to other components, and that has been achieved.

Regardless of whether the monopile decommissioning be will cost beneficial or not, the developers are obliged to decommission monopiles by law, while it is not the case when it comes to cables. The question remains, will the developers still consider decommissioning the cables even if a profit cannot be achieved with at least the total cost can be covered? As it can be seen that the cable decommissioning decision is mainly driven by regulation and possible cost.

5.3 Outlook

Given the immense development in the offshore wind industry, the number and capacity of offshore wind farms will continue to grow significantly. If the cable decommissioning issue will not be resolved by a more decisive regulatory framework, more cables will continue to be laid under the seabed. Thus, concerns of safety to shipping and navigation will increase significantly in the future with the increasing number of abandoned cables. Additionally, the right to use the seabed space might be another area of conflict in the long term as more cables will be landfilled into the sea.

However, a topic that worth further investigating at the moment is to study the entire life cycle of offshore cables and to estimate the amount of energy and CO2 emissions that can be saved if the offshore cables to be recycled instead of being abandoned at the seabed. That can involve estimating the amount of copper that already exist within the seabed from the offshore wind industry together with predicting the amount of copper to be used in the future based on the
current development of the industry. Such a study can provide a sustainable perspective on the benefits of cable recycling.

Another topic that can beneficial to the industry in terms of cost reduction is to study the impact of distance to the recycling port, size of cables, and the impact of economies of scale on the cable decommissioning cost, and subsequently to estimate at what point cable decommissioning can be economically beneficial. This can be achieved by taking a more detailed approach in calculating cost with consideration to the future development of cable recycling and removal techniques. As a result of such research, the developers will have more certainties in estimating the cable decommissioning cost at the early stage of development.
CHAPTER 6. CONCLUSIONS

The aim of this research is to provide an overview of the environmental and economic impact of cable decommissioning in offshore wind projects. In order to do so, a thorough review of the available literature has been conducted together with analyzing the ESs and decommissioning programs of existing OWFs.

The review of decommissioning standards and regulations have shown that international laws and conventions are somehow generic, and they do not provide a clear statement on the faith of the subsea cables when their life of service is over contrarily to the regulation of decommissioning other subsea components. That has led most local authorities to adopt a similar approach to evaluate the cable decommissioning on a case by case basis resulting, on most occasions, that cables are to be abandoned under the seabed. Such generic regulations can be considered a two-edged sword. On the one hand, it provides flexibility to the developers that can help reduce the overall cost of the offshore projects, given the technology is still developing, which can be beneficial. On the other hand, the absence of such regulations can accelerate the number of cables excising on the seabed significantly, leading to an increased risk to the safety of shipping and navigations and possibly unforeseen environmental and conflict of interest issues.

The flexibility of the regulations has led to three alternatives for cable decommissioning, namely total removal, partial removal, or leave all in place. The latter option and the partial removal are the most commonly adopted by the existing offshore wind projects and usually justified by environmental and technical cases that abandoning the cables is more beneficial than removing them. On the other hand, the total removal would involve unburying the cables, retrieve all the cable sections into a vessel and transport them to shore for recycling. Similar techniques will be used to remove the cables that involve ploughing, trenching, or water jetting, depending on the seabed lithology. The ploughs are preferable when it is possible as they have the ability to rebury the trench left behind cable pull out and are less disturbing than jetting and trenching. Moreover, it is possible to use the same cable installation vessel to remove the cable even though the requirements to remove the cables are less than installation.

The cables used in offshore wind farm projects come in a variety of sizes depending on the wind farm capacity. Copper is mainly used as a conductor in such cables and isolated with XLPE polymers that are covered with an outer shell composed of steel to protect the cables. The copper within the cables can be recycled endlessly; moreover, recycling copper requires
85% less energy than producing it from raw material, thus helping to reduce CO2 emissions. Copper prices are on the rise and projected to increase two folds in the coming years due to the increasing demand for products where copper is the primary material used, especially in the energy sector.

The removal of cables will be assassinated with an increase of suspended sediments, physical disturbance to benthic habitats, and chemical and noise pollutions. However, the reviewed literature has shown that any of these impacts are insignificant and can be neglected, regardless of the method used or the seabed lithology.

When analyzing the ESs and the decommissioning programs of the selected OWFs, it was found that all the environmental impact during cable installation, such as the increases in sediment concentrations and the disturbance to benthic ecology, is likely to occur and will have a direct impact on most cases. However, the impact level is found to be negligible in all aspects. Moreover, the impact during cable decommissioning was anticipated to be similar to cable installation, according to all the studied ESs. Nonetheless, when it comes to the decommissioning programs, the justification used to leave all cables in situ was that cable decommissioning would cause considerable damage to seabed ecology, which contradicts the findings in the ESs. Since such contradiction existed, it was unclear whether the decision behind the abandonment of cables was purely driven by environmental concerns or other technical or economic issues.

It was necessary to analyze the cost and benefits of removing the cables and compare that to the cost and benefits of removing the monopiles on an existing case to understand if the cable decommissioning can involve extreme costs that can make it unfeasible to remove. Moreover, the revenue generated from metal resell were considered to evaluate the cost reduction that can be achieved in both cases. Two values were assumed for copper scrap; the first value represents the current prices, whereas the second value was based on the prediction that copper prices to increase in the future.

It was found that the monopile decommissioning cost would share 24% of the total decommissioning cost, whereas the cable decommissioning cost would make up only 12% of the total cost. Regardless of the uncertainties due to the lack of data, the cable decommissioning cost is much less than decommissioning other subsea components, and it cannot be said as an extreme cost. Subsequently, the revenue from recycling the monopile can reduce the cost only
by 2%. Contrarily, the revenue generated from cable recycling can help reduce the total cost by up to 10%.

The cost of removing the monopiles outweigh tremendously the benefits that are generated from recycling, and it cannot be economically feasible even in the near future. However, it is removed due to regulatory obligations. Differently from the latter, cables decommissioning cost is less significant, and the benefits generated from recycling can cover almost all the decommissioning cost if copper prices increase as predicted. Additionally, and if we consider the current trend of cost reduction in the offshore wind industry, it is most likely that the cable decommissioning cost to be economically beneficial in the future.

It can be said that the cable decommissioning decision is mainly influenced by the lack of regulatory obligation and economic feasibility. Given most of the offshore wind farms to be decommissioned in the near and far future, it is recommended that the developers reconsider the cable decommissioning options in their final review of the decommissioning programs with keeping in mind to address the environmental impacts with more attentive description that can provide a thorough overview for the different stakeholders and enabling them to assess the environmental impact more precisely.

Moreover, the developer can play an important role in terms of cost reduction when considering removing the cables; a new market will be created to recycle subsea cables and will drive the development of new removal and more efficient recycling methods that will definitely make cables recovery from subsea economically feasible not to say beneficial.

Lastly, it is time for the regulatory bodies to review and update the usage of sea regulations as it is a new era where offshore energy development will play an important role in the coming decades that goes beyond laying few cables to connect remote islands or two countries. However, if new regulations to be set, they should be unified, clear, and fair for both the developers and environment and should be formulated in a way that does not hinder the current development of the renewable energy sector or contradicts the targets set by nations.
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