Economic and environmental assessments to support the decision-making process in the offshore wind farm decommissioning projects

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Abstract

The wind energy sector has experienced a significant expansion during the past two decades. With the current global appetite for the further expansion of Offshore Wind Farms (OWFs) as one of the main renewable energy resources, a vast number of OWFs are expected to enter the decommissioning stage in the near future which may potentially create serious environmental and economic challenges to different countries. Hence, effective decision-making procedures are required to protect the environment, taxpayers, and local communities against the potential economic and environmental impacts of OWF assets at the end of their lifetime. This study presents a new approach for economic and environmental assessments of OWF decommissioning projects based on a bottom-up model. The approach formulates the costs and emissions based on the available data and experience in the field and tries to provide appropriate assumptions to predict the costs and emissions caused by the different decommissioning activities. In order to validate and show the applicability of the approach, the cost and emission analyses of two OWF decommissioning case studies in the UK waters are investigated; the Lincs Limited and Gunfleet Sands OWFs. A cost sensitivity analysis is also performed for different duration and vessel/equipment leasing parameters to identify the most sensitive parameters in the OWF decommissioning projects. The study suggests a set of interesting conclusions on the economic and environmental assessment of OWF decommissioning projects that may be beneficial for policymakers, operators, and local communities in the wind energy sector.

Highlights

- The study provides economic and environmental assessments of OWF decommissioning projects
- The approach is developed based on the available data and experience in the field
- Two offshore wind farms, the Lincs Limited and Gunfleet Sands, are investigated.
- A sensitivity analysis of decommissioning costs for different parameters is performed.
- The study suggests interesting conclusions on the economic and environmental assessments

Keywords: Offshore wind farm, decommissioning, decision making, cost, emission

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Abbreviations

AWJC ....Abrasive Water Jet Cutting
BV..Barge Vessel
CBV ....Crane Barge Vessel
CLV ....Cable Laying Vessel
DCBV ....Derrick Crane Barge Vessel
DP ....Decommissioning Programme
IF ....Inflation Factor
JUV ....Jack-Up Vessel
MM..............................Meteorological Mast
NSR ....North Sea Region
O&G ....Oil and Gas
OS ....Offshore Substation
OSV ....Offshore Support Vessel
OWF ....Offshore Wind Farm
ROV ....Remotely Operated Vehicle
TB ....Tug Boat
WBS ....Work Breakdown Structure
WT..Wind Turbine

1. Introduction

The global offshore wind energy industry has witnessed a large expansion during the past two decades. Various countries across the world have set their roadmaps to expand their offshore wind energy resources in the coming decades. The UK is the global leader country in terms of the operational wind energy capacity with about 10.40 GW reported in 2020 [1], equivalent to 30% of global capacity. The UK government has recently announced an ambitious plan to boost its offshore wind energy capacity to 27.5 GW and 40 GW by 2026 and 2030, respectively [2]. The European Union countries with a total capacity of 14.6 GW in 2020 [1] are also planning to expand their offshore wind infrastructure further in the coming decades and achieve total capacity of 460 GW by 2050 [3–5].

Offshore Wind Farm (OWF) assets have also been developed technologically during the past decades which has reduced significantly wind energy production costs by up to 75% [6]. Currently, OWFs consist typically of large 7-9 MW Wind Turbines (WTs) that are installed in relatively shorter times than ever before [6]. Scotland is the home of the world's first commercial floating OWF, Hywind, which was commissioned officially in October 2017 [7]. Floating OWFs can be commissioned in significantly deeper water depths and longer distances from the shore which can potentially enhance the chance of capturing stronger wind energy resources.

The operational lifetime of an OWF is expected to be between 20 to 25 years [8,9]. However, due to the harsh weather conditions and site-specific characteristic features, there are a lot of uncertainties about their operational lifetime. At the end of their lifetimes, OWFs can be repowered through a set of amendments in their designs to extend their operational lifetime. However, due to the high repair or upgrade costs, repowering of OWFs is typically not an ideal option from the economic and technical viewpoints [10]. This leaves decommissioning as the only practical option for the end of the lifetime of OWFs, in which most of the offshore assets are dismantled/removed and a set of activities need to be performed to return the seabed to its original state. The current experience of the wind energy sector in decommissioning is limited, as only five small OWFs have been already dismantled worldwide [11]. In addition, as most previously decommissioned OWFs were in shallow waters with smaller assets in size and capacity, any previous experience is not fully applicable to the new OWF decommissioning projects [11]. In addition, OWF decommissioning includes a range of offshore operations performed by expensive vessels/equipment with the leasing rates highly sensitive to the market situation and technology availability. The advances in decommissioning technology, vessels, equipment, and recycling are also in the primary stage and significant developments are expected to take place in the coming years [12–14].

In addition to the significant expansion of offshore wind capacity in the past two decades, the global appetite for further expansion of OWFs highlights the fact that many OWFs are expected to enter the decommissioning stage in the future which might potentially create serious environmental and economic challenges to different countries [12,15]. The previous experience of Oil and Gas (O&G) and coal sectors in the US clearly show the extent of the decommissioning risk to the environment and different stakeholders, in which a massive number of sites and infrastructure were abandoned by bankrupt companies [16,17]. There are similar experiences in the offshore wind sector across the world which clearly show that the abandoned OWF assets can cause serious environmental challenges [17]. These show that there is an urgent need for effective and comprehensive OWF decommissioning regulations in order to protect the environment and taxpayers against the potential consequences of OWF assets at the end of their lifetime.

The UK is one of the leading countries that has developed its regulations and policies for OWF decommissioning. The Energy Act 2004 gives the power to the secretary of state for the department for Business, Energy and Industrial Strategy and Scottish ministers to request an appropriate form of financial security from OWF developers/owners with respect to their decommissioning obligations defined based on an agreed Decommissioning Programme (DP). According to the guidance recently published by the Scottish government [18], OWF owners/developers must provide the DP when they seek approval for the installation stage, which means that no installation operation will be allowed to take place without an already approved DP. In the prepared DP, the OWF owners/developers should predict the detailed decommissioning costs, techniques, and approaches [18]. Hence, the government should be able to check and confirm the predicted decommissioning costs by the OWF owner/developer to protect the taxpayers in the event the owner/developer defaults on their obligations. This shows how accurate cost modelling approaches play a crucial role in protecting the environment, taxpayers, and local communities against any unwanted consequences of OWF decommissioning projects.

The cost prediction of OWF decommissioning projects is rather difficult and highly dependent on a wide variety of parameters and assumptions. The OWF decommissioning is an emerging field with ongoing technological developments in which the available data and experience are quite limited [14,19]. The main goal of this study is to provide an approach for economic and environmental assessments of OWF decommissioning projects based on a bottom-up model. The approach is developed based on the available data and experience in the field and tries to provide appropriate assumptions to predict the costs and emissions caused by the different decommissioning operations. The study investigates two OWF case studies, the Lincs Limited and Gunfleet Sands OWFs, in the UK waters to investigate and validate the performance of the proposed approach. A sensitivity analysis of the overall decommissioning cost is also performed to identify key parameters affecting the cost assessment process.

The paper is organised as follows. The proposed cost assessment approach is presented in Section 2. The environmental assessment of decommissioning projects is investigated in Section 3 in which the detailed emission calculations for different operations are explained. In Section 4, the available data that can potentially affect the cost and emissions predictions are discussed. Section 5 investigates the performance of the proposed approach using two OWF case studies and discusses the decommissioning cost sensitivity analysis. Finally, Section 6 provides the concluding remarks.

2. Cost assessment

The OWF decommissioning stages can be described based on a Work Breakdown Structure (WBS). According to Milne et al. [14], the WBS for OWF decommissioning includes the project management, project preparation, offshore preparation, WT removal, Offshore Substation (OS) removal, Meteorological Mast (MM) removal, cable removal, seabed clearance and restoration, recycling and waste management, and monitoring. The focus of this study is on the removal operations of OWF decommissioning projects, including WT, OS, MM, and cable removals as well as seabed clearance and restoration. In this study, it is assumed that the removal of WT topsides and their foundations will be performed in separate operations. In the following subsections, the cost formulations for each removal operation will be presented based on a bottom-up model.

2.1. WT topside removal

The WT topside includes the blades, nacelle, and tower section. The different components of WT are usually lifted by a Jack-Up Vessel (JUV) and placed on a Barge Vessel (BV) pulled by Tug Boat (TB) for transportation to the shore. With these assumptions, the removal cost of the WT topsides can be expressed in terms of the mobilisation and day rates of mentioned vessels as follows:

$$C_{\mathrm{WT}} = C_{\mathrm{m}}^{\mathrm{JUV}} + \alpha C_{\mathrm{m}}^{\mathrm{BV}} + {}^{1}\!/_{24}\left(C_{\mathrm{D}}^{\mathrm{JUV}} + \alpha C_{\mathrm{D}}^{\mathrm{BV}} + \beta C_{\mathrm{D}}^{\mathrm{TB}}\right) t_{\mathrm{WT}}^{\mathrm{JUV}} \tag{1}$$

where, C_{WT} represents the removal cost of the WT topsides, $C_{\mathrm{m}}^{\mathrm{JUV}}$ and $C_{\mathrm{m}}^{\mathrm{BV}}$ are the mobilisation rates of JUV and BV, respectively, α represents the number of BVs, $C_{\mathrm{D}}^{\mathrm{JUV}}$, $C_{\mathrm{D}}^{\mathrm{BV}}$, and $C_{\mathrm{D}}^{\mathrm{TB}}$ are the day rates of the JUV, BV, and TB, respectively, β is the umber of TBs, and $t_{\mathrm{WT}}^{\mathrm{JUV}}$ is the total removal duration of WT topsides using JUV in hours. In this study, all the cost units are in pounds. The removal duration of WT topsides in the OWF, represented by t_{WT}, depends on the removal method, number of WTs, lifting durations, and vessel parameters. There are several WT removal methods defined based on reverse order of installation with different numbers of lifts and durations [20]. Due to the nature of the investigated case studies, it is assumed that the blades will be removed in three separate crane operations. Then, the nacelle with attached rotor and tower section will be lifted and placed on the BV in two separate lift operations. With this assumption, the total duration of WT topside removal can be calculated by the following formula:

$$t_{\mathrm{WT}}^{\mathrm{JUV}} = \gamma n_{\mathrm{t}}\left(t_{\mathrm{pos}}^{\mathrm{JUV}} + t_{\mathrm{up}}^{\mathrm{JUV}} + 3t_{\mathrm{B}} + t_{\mathrm{N}} + t_{\mathrm{T}} + t_{\mathrm{down}}^{\mathrm{JUV}}\right) \tag{2}$$

In the above equation, $\gamma > 1$ represents the parameter to consider the weather delays, n_{t} represents the number of WTs in the OWF, $t_{\mathrm{pos}}^{\mathrm{JUV}}$, $t_{\mathrm{up}}^{\mathrm{JUV}}$, and $t_{\mathrm{down}}^{\mathrm{JUV}}$ are the positioning, jacking-up, and jacking-down duration of JUV, respectively, t_{B} is the dismantling duration of each blade, t_N represents the removal duration of the nacelle, and t_{T} indicates the lifting duration of the tower section. It should be noted that all duration parameters in Equation (2) are in hours.

2.2. WT foundation removal

Foundation removal is one of the expensive operations in OWF decommissioning projects. It involves underwater pumping and cutting operations. It is also necessary to employ a Remotely Operated Vehicle (ROV) to support the underwater operations. The foundation removal operation consists of preparation and lifting stages. In the preparation stage, the mud inside the foundation is pumped out and the section of the monopile foundation is cut by using the Abrasive Water Jet Cutting (AWJC) technique. The latter stage includes the lifting of the foundation and placing it on a BV. Depending on the project strategy, the types of employed vessels for the foundation removal can vary. It is quite common to employ the JUV to perform both the preparation and cutting process (for example see Lincs DP [21]). However, due to the high day rate of JUVs, it would be better to minimise the waiting time of JUV during the preparation stage. As Kaiser and Snyder [20] argue, the foundation preparation stage can be done by an Offshore Support Vessel (OSV) which is much cheaper for lease compared to JUVs. In this study, it is assumed that the foundation preparation stage is performed by an OSV. Then, the JUV arrives at the site to lift and place the foundations on the BV. Hence, the applied vessels for the foundation removal process would be OSV, JUV, BV, and TB.

Considering the aforementioned points, the foundation removal cost can be formulated in terms of the vessel\equipment costs as:

$$= C_{\mathrm{m}}^{\mathrm{JUV}} + \alpha C_{\mathrm{m}}^{\mathrm{BV}} + C_{\mathrm{m}}^{\mathrm{ROV}} + C_{\mathrm{D}}^{\mathrm{OSV}} t_{\mathrm{F}}^{\mathrm{OSV}} + {}^{1}/_{24}\left(C_{\mathrm{D}}^{\mathrm{JUV}} + \alpha C_{\mathrm{D}}^{\mathrm{BV}} + \beta C_{\mathrm{D}}^{\mathrm{TB}}\right) t_{\mathrm{F}}^{\mathrm{JUV}} + {}^{1}/_{24} C_{\mathrm{D}}^{\mathrm{ROV}} \left(t_{\mathrm{F}}^{\mathrm{OSV}} + t_{\mathrm{F}}^{\mathrm{JUV}}\right) \quad (3)$$

In the above equation, C_{F} is the total cost of foundation removal, $C_{\mathrm{m}}^{\mathrm{ROV}}$ and $C_{\mathrm{D}}^{\mathrm{ROV}}$ represent the mobilisation cost and day rate of ROV, respectively, $C_{\mathrm{D}}^{\mathrm{OSV}}$ indicates the day rate of the OSV, $t_{\mathrm{F}}^{\mathrm{OSV}}$ the work duration of the OSV for foundation removal, $t_{\mathrm{F}}^{\mathrm{JUV}}$represents the work duration of the JUV for foundation removal, and the definitions for the rest of the parameters are similar to those explained in Section 2.1. The work duration of the OSV is calculated based on the time required for the pumping and cutting processes as follows:

$$t_{\mathrm{F}}^{\mathrm{OSV}} = \gamma n_{\mathrm{F}}\left(t_{\mathrm{pos}}^{\mathrm{OSV}} + t_{\mathrm{p}} + t_{\mathrm{c}} + t_{\mathrm{move}}^{\mathrm{OSV}}\right) \quad (4)$$

where, n_{F} represents the number of foundations in the OWF, $t_{\mathrm{pos}}^{\mathrm{OSV}}$ is the positioning duration of the OSV, t_{p} the time required to pump the mud inside the foundation, t_{c} is the time required for cutting the foundation section under the seabed, and $t_{\mathrm{move}}^{\mathrm{OSV}}$ is the time required by the OSV to move to the next foundation location. The cutting duration t_{c} can be obtained based on the cutting rate per the foundation diameter, represented by ν_{cut} in hr/m, as follows: $t_{\mathrm{c}} = \nu_{\mathrm{cut}} D$. The pumping duration t_{P} depends on the mud volume inside the foundation and can be calculated by the following equation:

$$t_{\mathrm{p}} = \frac{V_{\mathrm{p}}}{Q_{\mathrm{p}}} \tag{5}$$

where, V_{p} is the volume of the mud inside the foundation in m^3 and Q_{p} is the pumping rate in m^3/hr. The foundations are usually cut from a given depth under the seabed. The total mud volume that should be pumped can be calculated as follows:

$$V_{\mathrm{p}} = \frac{\pi}{4} D_{\mathrm{F}}^2 (d_{\mathrm{c}} + e) \tag{6}$$

where, D_{F} is the foundation diameter, d_{c} is distance of the cutting line from the seabed, and parameter e represents the additional space that should be provided for the cutter machine. In this study, it is assumed that the foundation will be cut from 1 m under the seabed (i.e., $d_{\mathrm{c}} = 1$ m), based on Ref. [22]. Moreover, the parameter e is taken as 1 m in this study.

As was mentioned earlier, the JUV will be employed to lift the foundation and place it on a BV deck space. The work duration of the JUV can be obtained by the following equation:

$$t_{\mathrm{F}}^{\mathrm{JUV}} = \gamma n_{\mathrm{F}} \left(t_{\mathrm{pos}}^{\mathrm{JUV}} + t_{\mathrm{up}}^{\mathrm{JUV}} + t_{\mathrm{L,F}}^{\mathrm{JUV}} + t_{\mathrm{down}}^{\mathrm{JUV}} \right) \tag{7}$$

where, $t_{\mathrm{L,F}}^{\mathrm{JUV}}$ is lifting duration of the foundation by the JUV and the definition for the rest of the parameters are similar to those in the previous section.

2.3. OS and MM removal

The removal process for the OS and MM consists of topside and foundation removal stages. The lifting operations in both stages are typically performed by the JUV. The dismantled components are transported to the shore by the BV supported by the required number of TBs. The removal cost of the OS can be written in terms of the vessel/equipment costs as:

$$C_{\mathrm{OS}} = C_{\mathrm{m}}^{\mathrm{JUV}} + C_{\mathrm{m}}^{\mathrm{ROV}} + C_{\mathrm{m}}^{\mathrm{BV}} + {}^{1}\!/_{24} \left(C_{\mathrm{D}}^{\mathrm{JUV}} + C_{\mathrm{D}}^{\mathrm{ROV}} + \alpha C_{\mathrm{D}}^{\mathrm{BV}} + \beta C_{\mathrm{D}}^{\mathrm{TB}} \right) t_{\mathrm{OS}}^{\mathrm{JUV}} \tag{8}$$

where, C_{OS} represents the removal cost of OS, $t_{\mathrm{OS}}^{\mathrm{JUV}}$ is the total removal duration of OS, and the definitions for the rest of the parameters are given in previous sections. Depending on the foundation type, the removal duration can be obtained by the following equations:

- *If the foundation of OS is a jacket structure*

$$t_{\mathrm{OS}}^{\mathrm{JUV}} = \gamma n_{\mathrm{OS}} \left(t_{\mathrm{pos}}^{\mathrm{JUV}} + t_{\mathrm{up}}^{\mathrm{JUV}} + t_{\mathrm{c,top}} + t_{\mathrm{L,top}} + t_{\mathrm{c,p}} + t_{\mathrm{L,J}} + t_{\mathrm{down}}^{\mathrm{JUV}} \right) \tag{9}$$

where, n_{OS} represents the number of OSs in the OWF, $t_{\mathrm{c,top}}$ is the time required to cut and disconnect the topside of the OS, $t_{\mathrm{L,top}}$ indicates the lifting duration of the OS topside, $t_{\mathrm{c,p}}$ is the time required for cutting the jacket piles under the seabed, and $t_{\mathrm{L,J}}$ is the time required to lift the jacket and place it on a BV.

- *If the foundation of OS is a monopile structure*

$$t_{\mathrm{OS}}^{\mathrm{JUV}} = \gamma n_{\mathrm{OS}}\left(t_{\mathrm{pos}}^{\mathrm{JUV}} + t_{\mathrm{up}}^{\mathrm{JUV}} + t_{\mathrm{c,top}} + t_{\mathrm{L,top}} + t_{\mathrm{p}} + t_{\mathrm{c}} + t_{\mathrm{L,F}}^{\mathrm{JUV}} + t_{\mathrm{down}}^{\mathrm{JUV}}\right) \quad (10)$$

where, t_{p} is the mud pumping duration obtained from Equation (5) and t_{c} is the foundation cutting duration which is assumed same as explained in Section 2.2.

The cost calculation for the MM removal operation is similar to the formulations provided above for the OS removal, but with significantly shorter duration parameters. As the topside and foundation of MM are significantly smaller in size and lighter in weights, the duration parameters $t_{\mathrm{c,top}}$, $t_{\mathrm{L,top}}$, t_{p} and t_{c} are expected to be shorter than those for the OS removal operation.

2.4. Cable removal

Current decommissioning regulations allow the cables to be left in their situation if they are buried at an appropriate depth under the seabed. Thus, the assumption of leaving cables in their situation is common in the recent OWF decommissioning programmes. In this case, a full inspection and burial are required, especially for the cable ends disconnected from the WTs. It is worth mentioning that the regulations on subsea cables may change and they might not be allowed to be left in place in future. Therefore, this study assumes that the cables will be removed entirely from the seabed, and the removal costs and emissions will be calculated.

The cable removal operation requires a Cable Laying Vessel (CLV) with subsea inspections performed by an ROV. The cost of cable removal operation can be obtained as follows:

$$C_{\mathrm{C}} = C_{\mathrm{m}}^{\mathrm{CLV}} + C_{\mathrm{m}}^{\mathrm{ROV}} + C_{\mathrm{D}}^{\mathrm{CLVi}} t_{\mathrm{I}}^{\mathrm{CLV}} + C_{\mathrm{D}}^{\mathrm{CLVe}} t_{\mathrm{E}}^{\mathrm{CLV}} + C_{\mathrm{D}}^{\mathrm{ROV}}\left(t_{\mathrm{I}}^{\mathrm{CLV}} + t_{\mathrm{E}}^{\mathrm{CLV}}\right) \quad (11)$$

where, C_{C} is the cable removal cost, $C_{\mathrm{m}}^{\mathrm{CLV}}$ is the mobilisation cost of the CLV, $C_{\mathrm{D}}^{\mathrm{CLVi}}$ and $C_{\mathrm{D}}^{\mathrm{CLVe}}$ are the day rates of the CLV for the inter-array and export cables, respectively, $t_{\mathrm{I}}^{\mathrm{CLV}}$ represents the removal duration of inter-array cables by a CLV, and $t_{\mathrm{E}}^{\mathrm{CLV}}$ is the removal duration of export cables using a CLV.

The cable removal is expected to take place in a relatively shorter time than the installation. Kaiser and Snyder [20] suggest converting the installation durations into the equivalent removal durations by using an Inflation Factor (IF) as the following equations:

$$t_{\mathrm{I}}^{\mathrm{CLV}} = \frac{L_{\mathrm{I}}}{r_{\mathrm{I}} IF_{\mathrm{I}}} \quad (12)$$

$$t_{\mathrm{E}}^{\mathrm{CLV}} = \frac{L_{\mathrm{E}}}{r_{\mathrm{E}} IF_{\mathrm{E}}} \quad (13)$$

In the above equations, L_{I} and L_{E} represent the lengths of inter-array and export cables, respectively, r_{I} indicates the inter-array cable installation rate in km/day, r_{E} is the installation rate for the export cables in km/day, IF_{I} and IF_{E} are inflation rates for the inter-array and export cables, respectively.

2.5. Seabed clearance and restoration

Following the completion of removal operations, a set of activities needs to take place to return the OWF site to its original state before the installation of assets. The holes resulting from the foundation removal need to be refilled and the scour protection around the foundations can be removed. As marine life typically forms on the scour protection over the lifetime of OWF, most of the OWF decommissioning projects have not been intended to remove the scour protection material on the seabed. This can be an ideal option from environmental and cost perspectives. However, this study assumes that the scour protection will be removed for assessment purposes.

The total cost of the seabed clearance and restoration activities can be simply written as:

$$C_{\mathrm{SC}} = C_{\mathrm{SP}} + C_{\mathrm{RD}} \tag{14}$$

where, C_{SC} is the total cost of the seabed clearance and restoration operations, C_{SP} represents the cost of the scour protection removal, and C_{RD} is the cost of rock dumping activities performed to refill the foundation location in the OWF site.

For the scour protection removal operation, a Derrick Crane Barge Vessel (DCBV) is employed. The removed scour materials are transported to the shore by a BV pulled by TBs. An ROV is also required for inspection and support of subsea activities. With these assumptions, the cost of scour protection removal operation can be formulated as:

$$C_{\mathrm{SP}} = C_{\mathrm{m}}^{\mathrm{DCBV}} + C_{\mathrm{m}}^{\mathrm{BV}} + \alpha C_{\mathrm{m}}^{\mathrm{ROV}} + {}^{1}/_{24}\left(C_{\mathrm{D}}^{\mathrm{DCBV}} + \alpha C_{\mathrm{D}}^{\mathrm{BV}} + \beta C_{\mathrm{D}}^{\mathrm{TB}} + C_{\mathrm{D}}^{\mathrm{ROV}}\right) t_{\mathrm{SP}}^{\mathrm{DCBV}} \tag{15}$$

in which:

$$t_{\mathrm{SP}}^{\mathrm{DCBV}} = (n_{\mathrm{t}} + n_{\mathrm{OS}} + 1)\left(t_{\mathrm{pos}}^{\mathrm{DCBV}} + t_{\mathrm{a}}^{\mathrm{DCBV}}\right) + \left(\sum_{i=1}^{n_{\mathrm{t}}} \frac{V_i^{\mathrm{WT}}}{r_{\mathrm{ret}}} + \sum_{i=1}^{n_{\mathrm{OS}}} \frac{V_i^{\mathrm{OS}}}{r_{\mathrm{ret}}} + \frac{V^{\mathrm{MM}}}{r_{\mathrm{ret}}}\right) \tag{16}$$

In Equations (15) and (16), C_{SP} is the overall cost of scour protection removal operation, $C_{\mathrm{m}}^{\mathrm{DCBV}}$ and $C_{\mathrm{D}}^{\mathrm{DCBV}}$ are the mobilisation cost and day rate of the DCBV, respectively, $t_{\mathrm{SP}}^{\mathrm{DCBV}}$ is the total removal duration of scour protection using a DCBV, $t_{\mathrm{pos}}^{\mathrm{DCBV}}$ represents the positioning duration of the DCBV, $t_{\mathrm{a}}^{\mathrm{DCBV}}$ represents the time required by the DCBV to retrieve its anchors, V_i^{WT} and V_i^{OS} are the volume of scour protection material around the ith WT and ith OS, respectively, V^{MM} is the scour protection material volume around the foundation of MM, r_{ret} indicates the removal rate of scour protection material, and the definitions for the other parameters are similar to those mentioned in the previous subsections.

The rock dumping cost can be calculated as follows:

$$C_{\mathrm{RD}} = C_{\mathrm{m}}^{\mathrm{RDV}} + C_{\mathrm{m}}^{\mathrm{ROV}} + \left(C_{\mathrm{D}}^{\mathrm{RDV}} + C_{\mathrm{D}}^{\mathrm{ROV}}\right) t_{\mathrm{RD}}^{\mathrm{RDV}} \tag{17}$$

in which:

$$t_{\mathrm{RD}}^{\mathrm{RDV}} = \frac{(n_{\mathrm{t}} + n_{\mathrm{OS}} + 1)}{r_{\mathrm{RD}}} \tag{18}$$

where, C_{RD} represents the cost of the rock dumping activity, $C_{\mathrm{m}}^{\mathrm{RDV}}$ is the mobilisation cost of the RDV, $C_{\mathrm{D}}^{\mathrm{RDV}}$ indicates the day rate of the RDV, $t_{\mathrm{RD}}^{\mathrm{RDV}}$ is the total rock dumping operation using a RDV, and r_{RD} is the rock dumping rate in locations per day.

2.6. Social Costs

The social cost is an attempt to put a price on emissions. The social cost assessment can be beneficial for policymakers to understand whether the costs and benefits of a proposed policy in expanding the OWFs to curb climate change are justified. The social costs related to the emission of various pollutants can be calculated by multiplying the emission values by the social cost factors listed in Table 1 [23]. In this study, the social costs will be calculated for the investigated case studies through the multiplication of the social cost factors in Table 1 by the emission amounts calculated from Section 3.

Table 1. Social cost factors for each pollutant [23]

Pollutant	Social cost per metric tonne
NO_x	£4,673
SO_x	£10,201
PM	£9,934
CO_2	£28.4

Note: The costs are converted from US dollars to British pounds @ 1$=0.71£

3. Environmental assessment

The emissions produced by decommissioning activities mainly depend on the fuel consumption and emission rates of the vessels/equipment involved in different operations. For each decommissioning activity, the overall emissions can be splitted into two parts, including the emissions resulting from the crane operations and the emissions produced by the transportation activities of dismantled components to the shore. In this section, the formulations for the emission calculation in different OWF decommissioning activities are presented.

The total emission amount produced by decommissioning activities can be simply written as:

$$E_{\mathrm{total}} = E_{\mathrm{WT}} + E_{\mathrm{F}} + E_{\mathrm{OS}} + E_{\mathrm{MM}} + E_{\mathrm{C}} + E_{\mathrm{SC}} \tag{19}$$

where, E_{total} represents the total emission amount, E_{WT}, E_{F}, E_{OS}, E_{MM}, E_{C}, and E_{SC} are the emissions produced by the WT removal, foundation removal, OS removal, MM removal, cable removal, and seabed clearance and restoration operations, respectively. The detailed formulations for each component of Equation (19) will be presented in the subsequent subsections.

3.1. WT removal emissions

The emissions produced by the WT removal operation E_{WT} can be expressed in terms of the emissions generated by the crane and transport operations as follows:

$$E_{\mathrm{WT}} = \mathrm{E}_{\mathrm{WT}}^{\mathrm{O}} + E_{\mathrm{WT}}^{\mathrm{tr}} \tag{20}$$

where, $\mathrm{E}_{\mathrm{WT}}^{\mathrm{O}}$ indicates the emissions produced by the lifting and positioning operations in WT removal operation and $E_{\mathrm{WT}}^{\mathrm{tr}}$ represents the emissions caused by the transportation of dismantled WT components to the shore. The emissions resulted from the crane operations $\mathrm{E}_{\mathrm{WT}}^{\mathrm{O}}$ are mainly related to the JUV, which can be expressed by the following equation:

$$\mathrm{E}_{\mathrm{WT}}^{\mathrm{O}} = 0.001 e_{\mathrm{r}} f_{\mathrm{JUV}} t_{\mathrm{WT}}^{\mathrm{JUV}} \tag{21}$$

where, $t_{\mathrm{WT}}^{\mathrm{JUV}}$ is the activity duration of JUV during the WT topside removal calculated from Equation (2), e_{r} is the emission factor for a given pollutant in kg/metric tonne, and f_{JUV} represents the fuel consumption rate of the JUV in tonne/hr.

The emissions of transportation activities depend on the project strategy. In this study, it is assumed that the dismantled components will be transported to the shore by using BVs pulled by TBs. Thus, the specifications of TBs should be considered in the transport emission calculations. The following equation expresses the transport emissions for the WT removal operation:

$$E_{\mathrm{WT}}^{\mathrm{tr}} = 0.001\, \beta e_{\mathrm{r}} f_{\mathrm{TB}} \left(t_{\mathrm{WT}}^{\mathrm{tr}} + t_{\mathrm{WT}}^{\mathrm{JUV}}\right) \tag{22}$$

where, β is the number of utilised TBs, f_{TB} is the fuel consumption rate of TB in tonne/hr, $t_{\mathrm{WT}}^{\mathrm{JUV}}$ is already known from Equation (2), and $t_{\mathrm{WT}}^{\mathrm{tr}}$ represents the transport duration of WT components to the shore. The transport duration $t_{\mathrm{WT}}^{\mathrm{tr}}$ depends on the deck capacity of the BV and removal strategy. Let us assume that the BV can carry the n_{CWT} number of WT topside units in each transport cycle. With this assumption, the transport duration $t_{\mathrm{WT}}^{\mathrm{tr}}$ can be calculated by the following equation:

$$t_{\mathrm{WT}}^{\mathrm{tr}} = \gamma \mathrm{fix}\left(\frac{n_{\mathrm{t}}}{n_{\mathrm{CWT}}}\right)\left(\frac{2 d_{\mathrm{port}}}{1.852 v_{\mathrm{TB}}} + n_{\mathrm{CWT}} t_{\mathrm{WT}}^{\mathrm{ol}} + t_{\mathrm{s}}\right) \tag{23}$$

where, γ is the weather delay parameter, $fix(.)$ is a function that rounds the input value to the nearest integer value, n_{t} is the number of WTs, d_{port} represents the distance between the port and OWF site, v_{TB} is the towing speed of the BVs in knots, $t_{\mathrm{WT}}^{\mathrm{ol}}$ represents the off-loading duration of each WT unit at the port, and t_{s} indicates the service time of the BV.

3.2. Foundation removal emissions

Similar to the previous subsection, the emissions produced by the foundation removal activities can be simply expressed in terms of the emissions resulting from the crane/cutting and transport activities as follows:

$$E_{\mathrm{F}} = E_{\mathrm{F}}^{\mathrm{O}} + E_{\mathrm{F}}^{\mathrm{tr}} \tag{24}$$

where, $E_{\mathrm{F}}^{\mathrm{O}}$ represents the emissions produced by the crane and cutting activities in foundation removal operation and $E_{\mathrm{F}}^{\mathrm{tr}}$ indicates the emissions generated by the transport operation of foundation units to the shore. As was explained in subsection 2.2, the JUV and OSV are involved in foundation removal operations. With this assumption, the emissions produced by crane and cutting operations can be written as follows:

$$E_{\mathrm{o}}^{\mathrm{F}} = e_{\mathrm{r}}\left(f_{\mathrm{OSV}} t_{\mathrm{F}}^{\mathrm{OSV}} + f_{\mathrm{JUV}} t_{\mathrm{F}}^{\mathrm{JUV}}\right) \tag{25}$$

where, f_{OSV} and f_{JUV} are the fuel consumption rates of the JUV and OSV in tonne/hr, respectively, $t_{\mathrm{F}}^{\mathrm{OSV}}$ is the activity duration of OSV known from Equation (4), and $t_{\mathrm{F}}^{\mathrm{JUV}}$ is the activity duration of JUV in the lifting operation of foundations obtained from Equation (7).

The emissions produced by the transport operation of dismantled foundations can be written as:

$$E_{\mathrm{F}}^{\mathrm{tr}} = \beta e_{\mathrm{r}} f_{\mathrm{TB}}\left(t_{\mathrm{F}}^{\mathrm{tr}} + t_{\mathrm{F}}^{\mathrm{JUV}}\right) \tag{26}$$

In the above equation, $t_{\mathrm{F}}^{\mathrm{JUV}}$ is known from Equation (7) and $t_{\mathrm{F}}^{\mathrm{tr}}$ represents the transport duration of foundation units to the port. Let n_{CF} be the number of foundation units transported by the BV in each transport cycle. Then, the transport duration can be calculated by the following formula:

$$t_{\mathrm{F}}^{\mathrm{tr}} = \gamma \mathrm{fix}\left(\frac{n_{\mathrm{F}}}{n_{\mathrm{CF}}}\right)\left(\frac{2d_{\mathrm{port}}}{1.852 v_{\mathrm{TB}}} + n_{\mathrm{CF}} t_{\mathrm{F}}^{\mathrm{ol}} + t_{\mathrm{s}}\right) \tag{27}$$

where, the definitions of all parameters were explained so far.

3.3. OS and MM removal emissions

As explained in Section 2.3, the OS and MM removal operations are similar with different duration parameters. In this subsection, the emission formulation for the OS removal operation will be discussed and similar equations can be used for the MM removal operation. The emissions for the OS removal operation, represented by E_{OS}, can be split up into two parts as follows:

$$E_{\mathrm{OS}} = E_{\mathrm{OS}}^{\mathrm{o}} + E_{\mathrm{OS}}^{\mathrm{tr}} \tag{28}$$

where, $E_{\mathrm{OS}}^{\mathrm{o}}$ is the emissions produced by the crane operations and $E_{\mathrm{OS}}^{\mathrm{tr}}$ is the emissions caused by the transportation of OS components. The emissions produced by the crane operations can be obtained by the following equation:

$$E_{\mathrm{o}}^{\mathrm{OS}} = e_{\mathrm{r}} f_{\mathrm{JUV}} t_{\mathrm{OS}}^{\mathrm{JUV}} \tag{29}$$

in which $t_{\mathrm{OS}}^{\mathrm{JUV}}$ is the activity duration of the JUV in OS removal operation obtained from equations (9) or (10), depending on the OS foundation type.

The transport emissions can be calculated by considering the TB fuel consumption as follows:

$$E_{\mathrm{OS}}^{\mathrm{tr}} = \beta e_{\mathrm{r}} f_{\mathrm{TB}}\left(t_{\mathrm{OS}}^{\mathrm{tr}} + t_{\mathrm{OS}}^{\mathrm{JUV}}\right) \tag{30}$$

where, $t_{\mathrm{OS}}^{\mathrm{tr}}$ is the duration required to transport the dismantled parts of the OS which is calculated by the following equation:

$$t_{\mathrm{OS}}^{\mathrm{tr}} = \gamma n_{\mathrm{OS}}\left(\frac{2d_{\mathrm{port}}}{1.852 v_{\mathrm{TB}}} + t_{\mathrm{OS}}^{\mathrm{ol,F}} + t_{\mathrm{OS}}^{\mathrm{ol,T}} + t_{\mathrm{s}}\right) \tag{31}$$

where, $t_{\mathrm{OS}}^{\mathrm{ol,F}}$ and $t_{\mathrm{OS}}^{\mathrm{ol,T}}$ are the offloading duration of the foundation and topside of the OS. In Equation (30), it is assumed that the TB will be in active mode during both crane and transport operations.

3.4. Cable removal emissions

For the cable removal operation, the emissions can be expressed in terms of the fuel consumption of CLV as:

$$E_{\mathrm{C}} = e_{\mathrm{r}} f_{\mathrm{CLV}} \left(t_{\mathrm{I}}^{\mathrm{CLV}} + t_{\mathrm{E}}^{\mathrm{CLV}} \right) \tag{32}$$

where, f_{CLV} is the fuel consumption of the CLV in tonne/hour, $t_{\mathrm{I}}^{\mathrm{CLV}}$ represents the time required for the removal of inter-array cables known from Equation (12), and $t_{\mathrm{E}}^{\mathrm{CLV}}$ indicates the removal duration of the export cables obtained from Equation (13).

3.5. Emissions for the seabed clearance and restoration

As was discussed earlier in Section 2.5, the seabed clearance and restoration include the scour protection removal and rock dumping operations. Hence, the emission for these activities can be expressed as:

$$E_{\mathrm{SC}} = E_{\mathrm{SP}} + E_{\mathrm{RD}} \tag{33}$$

where, E_{SC} is the emissions produced by the seabed clearance and restoration activities, E_{SP} represents the emissions caused by the scour protection removal, and E_{RD} is the emissions resulting from the rock dumping operation.

The emissions produced by the scour protection removal E_{SP} can be written in terms of the emissions caused by operational and transport operations as:

$$E_{\mathrm{SP}} = E_{\mathrm{SP}}^{\mathrm{O}} + E_{\mathrm{SP}}^{\mathrm{tr}} \tag{34}$$

where, $E_{\mathrm{SP}}^{\mathrm{O}}$ is the emissions produced by the scour protection removal operation and $E_{\mathrm{SP}}^{\mathrm{tr}}$ indicates the emissions caused by the transportation of removed materials. The emissions resulted from the scour protection removal operation $E_{\mathrm{SP}}^{\mathrm{O}}$ can be calculated as follows:

$$E_{\mathrm{SP}}^{\mathrm{O}} = e_{\mathrm{r}} f_{\mathrm{DCBV}} t_{\mathrm{SP}}^{\mathrm{DCBV}} \tag{35}$$

where, f_{DCBV} represents the fuel consumption of the DCBV in tonnes/hr and $t_{\mathrm{SP}}^{\mathrm{DCBV}}$ indicates the total removal duration of the scour protections calculated from Equation (16). As the BV is used for the transport of removed materials, the emission $E_{\mathrm{SP}}^{\mathrm{tr}}$ can be written as:

$$E_{\mathrm{SP}}^{\mathrm{tr}} = \beta e_{\mathrm{r}} f_{\mathrm{TB}} t_{\mathrm{SP}}^{\mathrm{DCBV}} \tag{36}$$

where, f_{TB} represents the fuel consumption rate of the TB in tonnes/hr. In the above equation, it is assumed that the TB will be in an active mode during the whole operation.

The emissions caused by the rock dumping activity E_{RD} can be obtained by the following equation:

$$E_{\mathrm{RD}} = e_{\mathrm{r}} f_{\mathrm{RDV}} t_{\mathrm{RD}}^{\mathrm{RDV}} \tag{37}$$

where, f_{RDV} represents the fuel consumption of the RDV in tonnes/hr and $t_{\mathrm{RD}}^{\mathrm{RDV}}$ is the total rock dumping duration obtained from Equation (18).

4. Parameters

The cost and emission formulations depend on a variety of durations, leasing, emission, and fuel consumption parameters which can significantly affect the cost and emission estimations. In the following subsection, the assumed ranges for these parameters are presented based on different sources.

4.1. Cost parameters

The costs of decommissioning operations depend on the duration and vessels/equipment leasing parameters. In this subsection, the possible ranges for these parameters are discussed. As was mentioned earlier, the lack of available information is one of the key barriers to the development of accurate cost models for OWF decommissioning projects. The information depends primarily on the geographical location of the OWF, utilised technology, availability of vessels/equipment, weather conditions, project planning, market conditions, etc. In this study, the experience and information gathered from different available studies and technical reports are employed to provide the best possible cost and emission estimations. Table 2 presents the available ranges for the different duration parameters in each decommissioning activity. This table reflects the fact that the assumptions for time parameters are subjected to significant uncertainties due to weather conditions. In addition, Table 3 lists possible ranges for the leasing parameters of vessels/equipment based on a variety of sources. It is observable that the available experience offers wide intervals for the leasing costs which makes the development of an accurate cost estimation a rather difficult task. The leasing costs depend on the contract duration, supply and demand balance in the market, the situation of the O&G industry, etc. Based on Table 2 and Table 3, appropriate values are assumed in this study for the parameters with no historically available values.

Table 2. The available and assumed values for duration parameters in different decommissioning activities

Activity	Parameter	Unit	Description	Parameter ranges	
				Minimum	Maximum
WT removal	$t_{\mathrm{pos}}^{\mathrm{JUV}}$	hr	Positioning duration of the JUV	3.00 [24]	8.00 [24]
	$t_{\mathrm{up}}^{\mathrm{JUV}}$	hr	Jacking-up duration of the JUV	6.00 [24]	10.00 [24]
	$t_{\mathrm{down}}^{\mathrm{JUV}}$	hr	Jacking-down duration of the JUV	1.00 [24]	4.00 [24]
	t_{s}	hr	The service time of the BV at port	24 [21]	-
	t_{B}	hr	Removal duration of an individual blade	2.00 [24]	3.33 [24]
	t_{N}	hr	Removal duration of the nacelle	2.50 [24]	6.00 [24]
	t_{T}	hr	Removal duration of both tower segments in a single lift	6.00 [25]	6.00 [25]
	n_{CWT}	-	The number of WT topside units in each transport cycle	2*	5*
	$t_{\mathrm{WT}}^{\mathrm{ol}}$	hr/unit	Off-loading duration of each WT unit at the port	12 [21]	-
	v_{BV}	knots	Towing speed of BVs	5*	10*
Foundation removal	$t_{\mathrm{pos}}^{\mathrm{OSV}}$	hr	Positioning duration of the OSV	0.25 [20]	2.00 [26]
	$t_{\mathrm{move}}^{\mathrm{OSV}}$	hr	Moving duration of the OSV	0.25 [26]	2.00 [20]
	v_{cut}	hr/m	Cutting speed per foundation diameter	10.00 [26]	24.00 [26]
	Q_{p}	m³/hour	Pumping rate	25.00 [26]	50.00 [26]
	$t_{\mathrm{L,F}}^{\mathrm{JUV}}$	hr	Lifting duration of the foundation	2.00 [26]	8.00 [26]
	n_{CF}	-	The number of foundation units transported by the BV in each transport cycle	5*	10*
	$t_{\mathrm{F}}^{\mathrm{ol}}$	hr/unit	Off-loading duration of each WT unit at the port	2.4 [21]	-
Cable removal	r_{I}	km/day	Installation rate of inter-array cables	0.15 [26]	0.60 [26]
	r_{E}	km/day	Installation rate of export cables	0.20 [26]	1.40 [26]
	IF_{I}	-	Inflation rate for inter-array cables	1.50 [26]	3.00 [26]
	IF_{E}	-	Inflation rate for export cables	1.00 [26]	2.00 [26]
OS removal	$t_{\mathrm{c,top}}$	hr	Cutting and disconnecting duration required for the topside removal of OS	12.00 [26]	-
	$t_{\mathrm{L,top}}$	hr	Lifting duration of the topside of OS by the JUV	3.00 [26]	-
	$t_{\mathrm{c,p}}$	hr	Cutting duration of the jacket piles under the seabed	48.00 [26]	-
	$t_{\mathrm{L,J}}$	hr	The time required by the JUV to lift the jacket structure	3.00 [26]	-
	$t_{\mathrm{OS}}^{\mathrm{ol,F}}$	hr	Off-loading duration of each OS foundation unit at the port	3*	-
	$t_{\mathrm{OS}}^{\mathrm{ol,T}}$	hr	Off-loading duration of each OS topside unit at the port	8*	-
MM removal	$t_{\mathrm{c,top}}$	hr	Cutting and disconnecting duration required for the topside removal of MM	4.00 [26]	-
	$t_{\mathrm{L,top}}$	hr	Lifting duration of the topside of MM by the JUV	3.00 [26]	-
	$t_{\mathrm{ol,F}}^{\mathrm{MM}}$	hr	Offloading duration per MM foundation at the port	2.4*	-
	$t_{\mathrm{ol,T}}^{\mathrm{MM}}$	hr	Offloading duration per MM topside unit at the port	2.4*	-
Seabed clearance and restoration	$t_{\mathrm{pos}}^{\mathrm{DCBV}}$	hr	Positioning duration of the DCBV to start the removal operation	6.00 [27]	-
	r_{ret}	m³/hour	The removal rate of scour protection materials	144.00 [27]**	-
	r_{RD}	Locations /day	Rock dumping rate	8 [27]	-
	$t_{\mathrm{a}}^{\mathrm{DCBV}}$	hr	The time required by the DCBV to retrieve its anchors	8.00 [27]	-

*Assumed in this study
**According to the DP of the Cape Wind [27], with the assumption of the clamshell bucket with a capacity of 6 m³, by assuming 2.5 minutes for fill and dump duration, the removal rate of scour protection materials would be roughly 144 m³/hour.

Table 3. Available and assumed values for the vessel/equipment rates

Vessel/equipment	Mobilisation/Demobilisation		Day rates	
	Notation	Rate (£)	Notation	Rate (£)
JUV	$C_{\mathrm{m}}^{\mathrm{JUV}}$	400k-445k [28]	$C_{\mathrm{D}}^{\mathrm{JUV}}$	200k [29][1] 100k-125k [28] 138.8k-169k[2] [30]
CLV	$C_{\mathrm{mob}}^{\mathrm{CLV}}$	445k [28]	$C_{\mathrm{D}}^{\mathrm{CLV}}$	80k (inter), 100k (export) [28] 40k-50k [29][1] 78.5k (inter), 98.27k (export) [31][2]
OSV	$C_{\mathrm{m}}^{\mathrm{OSV}}$	N/A	$C_{\mathrm{D}}^{\mathrm{OSV}}$	3.9k [32][2]
DCBV	$C_{\mathrm{m}}^{\mathrm{DCBV}}$	100k[3]	$C_{\mathrm{D}}^{\mathrm{DCBV}}$	50k [29][1]
RDV	$C_{\mathrm{m}}^{\mathrm{RDV}}$	10.6k [28]	$C_{\mathrm{D}}^{\mathrm{RDV}}$	11.9k [31] [2] 13.8k [28]
BV	$C_{\mathrm{m}}^{\mathrm{BV}}$	172.4k [32][2]	$C_{\mathrm{D}}^{\mathrm{BV}}$	30k [31] [2] 12.9k [32][2]
TB	$C_{\mathrm{m}}^{\mathrm{TB}}$	N/A	$C_{\mathrm{D}}^{\mathrm{TB}}$	13.8k-15.5k [30][2] 19.4k [31][2] 8.6k [32][2]
ROV	$C_{\mathrm{m}}^{\mathrm{ROV}}$	34.48k [32] [2]	$C_{\mathrm{D}}^{\mathrm{ROV}}$	20k-40k [29][1] 3.45k [32] [2]

[1]Based on the 2017 market
[2]Exchanges rate is applied: 1£=1.16€
[3]Assumed due to the lack of the data

4.2. Fuel consumption rates and emission factors

The emission formulations depend on the emission factor and fuel consumption rates. The emission factor varies depending on the type of pollutant. Table 4 lists the emissions factors for different pollutants. The fuel consumption rates depend on the vessel type as well as the activity mode. In this study, an average value of fuel consumption is assumed for each vessel as listed in Table 5.

Table 4. Emission factors for different pollutants in kg/metric tonne [33]

Pollutant	Emission factor (e_{r})
NO_x	61
SO_x	9.2
PM	1.7
CO_2	3,190

Table 5. Fuel consumption parameters for different vessels [34]

Fuel parameter	Fuel type	Fuel consumption (tonne/hour)
f_{TB}	MGO	0.32
f_{JUV}	HFO	0.41*
f_{OSV}	MGO	0.41*
f_{CLV}	MGO	0.45
f_{RDV}	HFO	0.21
f_{DCBV}	HFO	0.36

*Assumed in this report based on average fuel consumption of 10 tonnes/day

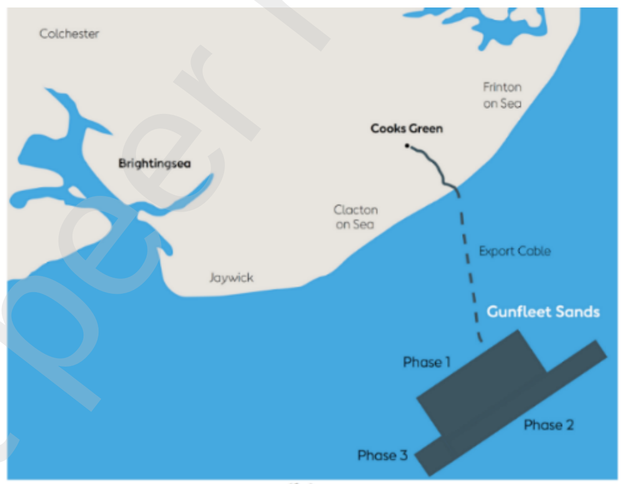
5. Case studies

In this section, the cost and environmental assessments of two OWF decommissioning case studies in the UK are investigated. Both OWFs consist of WTs with individual capacities of 3.6 MW. The Gunfleet Sands OWF is the first case study, which is used to show how the uncertainties in the duration and leasing parameters can cause dramatic changes in the cost and emission estimations. In the Lincs Limited OWF, the cost and emissions are more realistic, and the results are verified by the cost estimation available from the source reports. The overall intention of this section is to provide the cost and emission estimations for the mentioned OWFs based on their real site-specific information. In the investigated case studies, the constant social cost, emission, and fuel consumption rates listed in Table 1, Table 4, and Table 5 are used.

5.1. Gunfleet Sands OWF

The Gunfleet Sands OWF is located 8.5 km off the southeast coast of Clacton-on-Sea, Essex, UK. The installation process of this OWF took place in three different phases. The location and different installation phases of Gunfleet Sands OWF are illustrated in Figure 1. The first and second phases inaugurated in 2010 consist of 30 and 18 WTs, respectively. Two additional 6 MW WTs were also installed in 2013 for demonstration purposes. The initial design lifetime of this OWF was considered to be 20 years [35]. Figure 2 illustrates the overall layout of the Gunfleet Sands OWF. In this study, the first two phases are considered for the decommissioning cost and environmental assessments.

(a)



(b)

Figure 1. The Gunfleet Sands OWF: (a) location (Google map), (b) different phases [36]

The general information of the Gunfleet Sands OWF assets is presented in Table 6. The foundation type of the WTs is a steel monopile structure with the specifications listed in Table 7. The initial environmental assessment report of this OWF published in 2007 [37] has set few decommissioning objectives. However, appropriate assumptions need to be made for most decommissioning activities. In this study, a set of assumptions are considered for different decommissioning activities in the Gunfleet Sands OWF as presented in Table 8. The assumptions in Table 8 were adopted by considering the available limited information from the installation phase in Refs. [37,38].

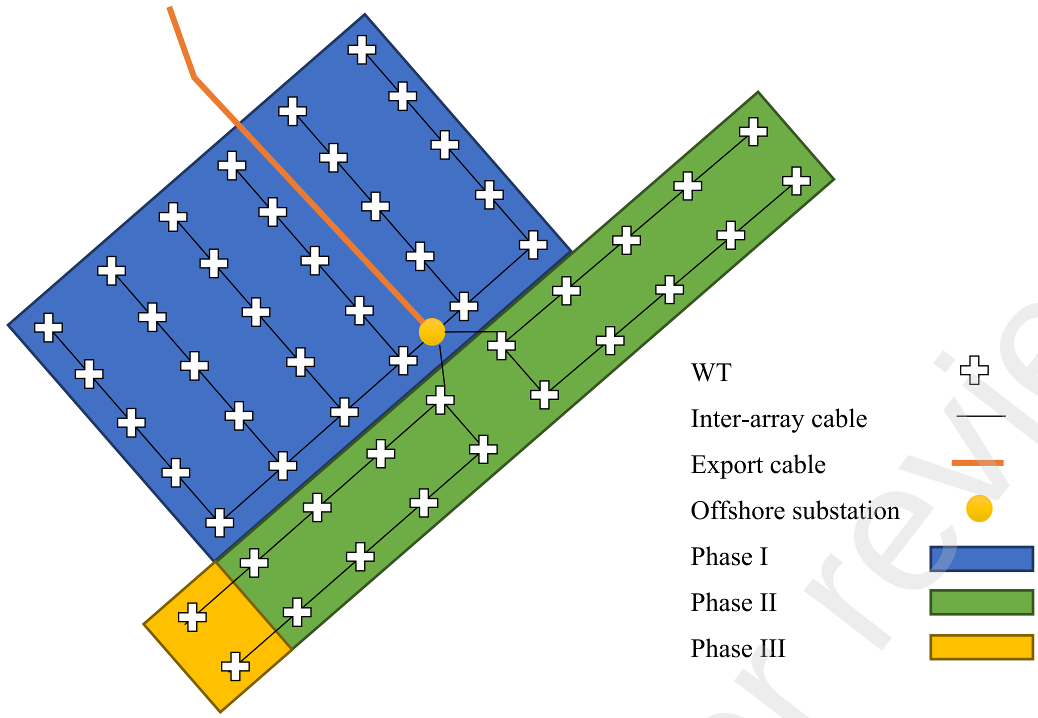


Figure 2. The WT and cable layouts in the Gunfleet Sands case study

Table 6. General information of the Gunfleet Sands OWF assets [35,37]

	Specifications	Description
General	Distance to shore	8.5 km from the south-east of Clacton-on-Sea, Essex, UK
	No. of OS	1
	Export cable	9.3 km
	Inter-array cables	Sea-armoured 3 core copper XLPE with a total length of 34 km
	No. of MM	1
	Water depth	2-15 m
	Scour protection	150-1000 m^3 (average value of 575 m^3 per foundation is assumed in this study)
Phase I (GS-I)	No. of WTs	30×3.6MW
	WTs spacing	435×890 m
	WT type	Siemens Wind Power SWT-3.6-107
	Site area	10 km^2
Phase II (GS-II)	No. of WTs	18×3.6MW
	WTs spacing	435×890 m
	WT type	Siemens Wind Power SWT-3.6-107
	Site area	7.5 km^2

Table 7. The specifications for monopile foundations in the Gunfleet Sands OWF [35]

	Specifications	Description
Dimensions	Outer shaft diameter	4.5-5 m
	Shaft wall thickness	0.06-0.1 m
	Overall length	50-75 m
	Seabed penetration	up to 50 m
	Weight	300-700 tonnes depending on the depth
Material (per monopile)	Steel	300-700 tonnes
	Concrete	For fixing of transition piece: 25-100 tonnes
	Gravel/Rock	For scour protection of monopiles: 150–1000 m^3

Table 8. The decommissioning strategies assumed in this study for the Gunfleet Sands case study

Asset	Installation techniques and equipment [37,38]	Decommissioning assumptions adopted in this study
WTs	• A JUV employed for installation • Installation method: Tower+Nacelle+Blade+ Blade+Blade	• Reverse order of installation is considered for WT removal • A JUV was assumed for lifting operations and two BVs were assumed for transportation. TBs are also required.
Monopiles and transition pieces	The installation of the monopiles and transition pieces was performed by the Crane Barge Vessel (CBV) and JUV in deeper and shallower waters, respectively.	• Internal cutting for monopile removal is assumed • AWJC tool will be used for cutting the monopile • The mud inside the monopile needs to be pumped up to 1 m below the cutting line • It is assumed that the foundation will be cut from 1 or 2 m below the seabed • An OSV will be used to support cutting operations and a JUV is assumed for foundation liftings • It is assumed that a single BV towed by a TB will be used for transportation
OS and MM	No available data	• An ROV is required for subsea inspections • A JUV is assumed for lifting topside and jacket structures • A BV pulled by a TB is considered for the transportation • A ROV is needed for subsea inspection
Cables	No available data	• Complete cable removal is considered in this study • Subsea survey will be performed using ROV • A CLV will be required for cable retrieval
Scour protection	No available data	• Total removal is considered in this study • A DCBV is needed • A BV towed by a TB is employed for transportation • A RDV is considered for filling the foundation locations after foundation removal operations

In this case study, the decommissioning costs and emissions are calculated for the minimum and maximum cost scenarios to show how the uncertainties in available data can affect the results. In the minimum cost scenario, the shortest durations and cheapest vessel/equipment leasing rates in Table 2 and Table 3 are assumed, while the longest duration and most expensive vessel/equipment leasing rates are selected from Table 2 and Table 3 for the maximum costs scenario. In both cases, a 20% delay in operational times is considered due to weather conditions (i.e., $\gamma = 1.20$). Table 9 lists the minimum and maximum leasing rates assumed for different vessels/equipment in this case study. The values in Table 9 are selected based on the previous experience presented in Table 3. The durations and costs calculated for each decommissioning activity are presented in Table 10. The overall observation from Table 10 suggests that the costs and operational durations are significantly sensitive to the variations in the available data. The average WT removal duration from 1.225 days/turbine in the minimum scenario increases to 2.15 days/turbine in the maximum scenario, showing about 75% changes in terms of the duration. However, the change in the cost of WT removal operation in the whole OWF is more dramatic, increasing from £9.1m to £31.6m, which shows more than a 300% increase in the cost value. A similar conclusion can be made for the other activities. It is worth mentioning that the change in the cable removal cost value is surprisingly large which highlights the level of uncertainty of available data for this activity. Figure 3 illustratively compares the minimum and maximum costs for each activity.

Table 9. The vessel/equipment leasing rates assumed for the minimum and maximum cost scenarios in the Gunfleet Sands case study

Activity	Vessel type	Quantity	Mobilisation/Demobilisation (£)		Day rate (£)	
			Minimum	Maximum	Minimum	Maximum
WT removal	JUV	1	400 k	445 k	100 k	200 k
	BV	2	172.4 k	172.4 k	12.9 k	30 k
	TB	2	N/A	N/A	8.6 k	19.4 k
Foundation removal	JUV	1	400 k	445 k	100 k	200 k
	OSV	1	N/A	N/A	3.9 k	3.9 k
	BV	1	172.4 k	172.4 k	12.9 k	30 k
	TB	1	N/A	N/A	8.6 k	19.4 k
	ROV	1	34.48 k	34.48 k	3.45 k	40 k
OS and MM removals	JUV	1	400 k	445 k	100 k	200 k
	BV	1	172.4 k	172.4 k	12.9 k	30 k
	TBs	1	N/A	N/A	8.6 k	19.4 k
	ROV	1	34.48 k	34.48 k	3.45 k	40 k
Cable removal	CLV (inter)	1	445 k	445 k	40 k	98.27 k
	CLV (export)	1	445 k	445 k	40 k	78.5 k
	ROV	1	34.48 k	34.48 k	3.45 k	40 k
Seabed clearance and restoration	DCBV	1	100 k	100 k	50 k	50 k
	RDV	1	10.6 k	10.6 k	11.9 k	13.8 k
	BV	1	172.4 k	172.4 k	12.9 k	30 k
	ROV	1	34.48 k	34.48 k	3.45 k	40 k
	TB	1	N/A	N/A	8.6 k	19.4 k

Table 10. The costs and durations calculated for different decommissioning activities in the Gunfleet Sands case study

Activity		Total duration (days)	Weather delay (%)	Duration including weather delay (days)	Duration per unit (days/unit)	Removal cost (£)
WT removal	Minimum	49.00	20%	58.80	1.225	9,153,200
	Maximum	85.98	20%	103.17	2.15	31,618,788
Foundation removal	Minimum	102.57 (OSV) 34.20 (JUV)	20%	123.08 (OSV) 41.03 (JUV)	2.56 (OSV) 0.85 (JUV)	6,638,188
	Maximum	251.14 (OSV) 68.38 (JUV)	20%	301.37 (OSV) 82.05 (JUV)	6.28 (OSV) 1.71 (JUV)	37,629,883
OS removal	Minimum	3.24	20%	3.89	3.89	1,108,012
	Maximum	6.90	20%	8.28	8.28	3,079,975
MM removal	Minimum	2.49	20%	2.99	2.99	384,890
	Maximum	5.48	20%	6.57	6.57	1,928,226
Cable removal	Minimum	18.9 (inter) 3.32 (export)	20%	22.67 (inter) 3.99 (export)	0.67 day/km (inter) 0.43 day/km (export)	1,637,525
	Maximum	151.11 (inter) 46.50 (export)	20%	181.33 (inter) 55.80 (export)	5.42 day/km (inter) 6 day/km	32,164,740
Seabed clearance and restoration	Minimum	37.49 (scour protection) 6.25 (rock dumping)	20%	44.98 (scour protection) 7.5 (rock dumping)	120 m^3/hour (scour protection) 6.67 locations/day (rock dumping)	4,065,179 (scour protection) + 99,850 (rock dumping) = 4,472,833
	Maximum	37.49 (scour protection) 6.25 (rock dumping)	20%	44.98 (scour protection) 7.5 (rock dumping)	120 m^3/hour (scour protection) 6.67 locations/day (rock dumping)	7,450,123 (scour protection) + 114,100 (rock dumping) = 7,564,223

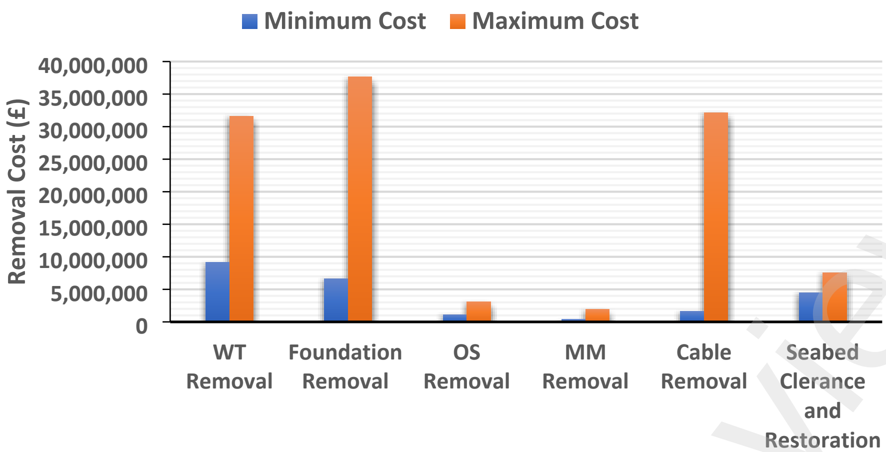


Figure 3. The removal cost comparisons between the minimum and maximum cost scenarios in the Gunfleet Sands case study

As shown in the emission formulations presented in Section 3, the emission amounts can be affected by the uncertainties in duration parameters. To investigate the extent of emissions' sensitivity to the uncertainties in duration parameters, the detailed emissions of different pollutants produced by decommissioning activities for the two scenarios are presented in Table 11 and Table 12, respectively. The results provide the transport, operational, and overall emissions. From Table 11 and Table 12, it can be observed that the overall CO_2 emission increases from 17,912 tonnes in the minimum scenario to 37,919 tonnes in the maximum scenario, about a 111% change in emission amounts. Although the differences in emission amounts obtained from the two scenarios are remarkable, the effects of uncertainties in initial data on the emissions are not as great as their impact on the cost values. Table 13 and Table 14 present the social costs caused by the different pollutants in minimum and maximum cost scenarios, respectively. These tables show that the social costs are about £2.76 m and £5.78 m for the minimum and maximum scenarios, respectively. Similar to the emission amounts, the changes in the social costs due to uncertainties in duration parameters are also more than 100%. It can also be seen that NOx is a major contributor to the social cost values. The removal and social costs are combined and the percentage break-down distributions for different cost items are presented in Figure 4 and Figure 5. From these figures, the social costs account for about 10% and 5% of total removal costs in the minimum and maximum scenarios, respectively. Once again, these figures show that the cable removal costs are significantly different in the two scenarios, showing the impact of high uncertainties in the cable removal rate parameters.

Table 11. The emissions of different activities in the minimum cost scenario for the Gunfleet Sands case study (tonnes)

Activity	Emissions	NOx	SO_X	PM	CO_2
WT removal	E_{WT}^{tr}	94.88	14.31	2.64	4962
	E_{WT}^{O}	35.29	5.32	0.98	1846
	E_{WT}	130.18	19.63	3.63	6808
Foundation removal	E_{F}^{tr}	19.22	2.90	0.54	1,005
	E_{F}^{O}	98.51	14.86	2.75	5152
	E_{F}	117.73	17.76	3.28	6157
OS removal	E_{OS}^{tr}	2.66	0.40	0.07	139
	E_{OS}^{o}	2.33	0.35	0.07	122
	E_{OS}	4.99	0.75	0.14	261
MM removal	E_{MM}^{tr}	2.10	0.32	0.06	110
	E_{MM}^{o}	1.79	0.27	0.05	94
	E_{MM}	3.89	0.59	0.11	204
Cable removal	E_{C}	17.56	2.65	0.49	918
Seabed clearance and restoration	E_{SP}^{tr}	42.15	6.36	1.18	2,204
	E_{SP}^{O}	23.71	3.58	0.66	1240
	E_{SP}	65.86	9.93	1.84	3444
	E_{RD}	2.31	0.35	0.06	121
	E_{SC}	68.17	10.28	1.90	3565
Total:		342.51	51.66	9.55	17,912

Table 12. The emissions of different activities in the maximum cost scenario for the Gunfleet Sands case study (tonnes)

Activity	Emissions	NOx	SO_X	PM	CO_2
WT removal	E_{WT}^{tr}	152.74	23.04	4.26	7987
	E_{WT}^{O}	61.93	9.34	1.73	3239
	E_{WT}	214.67	32.38	5.98	11,226
Foundation removal	E_{F}^{tr}	38.44	5.80	1.07	2010
	E_{F}^{O}	230.15	34.71	6.41	12,036
	E_{F}	268.59	40.51	7.48	14,046
OS removal	E_{OS}^{tr}	4.74	0.72	0.13	248
	E_{OS}^{o}	4.97	0.75	0.14	260
	E_{OS}	9.71	1.47	0.27	508
MM removal	E_{MM}^{tr}	3.80	0.57	0.11	199
	E_{MM}^{o}	3.95	0.60	0.11	206
	E_{MM}	7.74	1.17	0.22	405
Cable removal	E_{C}	156.22	23.56	4.35	8170
Seabed clearance and restoration	E_{SP}^{tr}	42.15	6.36	1.18	2204
	E_{SP}^{O}	23.71	3.58	0.66	1240
	E_{SP}	65.86	9.93	1.84	3444
	E_{RD}	2.31	0.35	0.06	121
	E_{SC}	68.17	10.28	1.90	3565
Total:		725.10	109.36	20.21	37,919

Table 13. The social costs caused by the different pollutants for the minimum cost scenario in the Gunfleet Sands case study

Activity	Social costs (£)				
	NOx	SO_X	PM	CO_2	Total
WT removal	608,313	200,277	36,039	193,335	1,037,964
Foundation removal	550,150	181,128	32,593	174,850	938,721
OS removal	23,357	7,690	1,384	7,423	39,853
MM removal	18,173	5,983	1,077	5,776	31,008
Cable removal	82,051	27,014	4,861	26,077	140,004
Seabed clearance and restoration	318,513	104,865	18,870	101,230	543,480
Total:	1,600,557	526,958	94,824	508,692	**2,731,030**

Table 14. The social costs caused by the different pollutants for the maximum cost scenario in the Gunfleet Sands case study

Activity	Social costs (£)				
	NOx	SO_X	PM	CO_2	Total
WT removal	1,003,133	330,266	59,430	318,817	1,711,646
Foundation removal	1,255,132	413,232	74,360	398,908	2,141,632
OS removal	45,379	14,940	2,689	14,423	77,430
MM removal	36,189	11,915	2,144	11,502	61,749
Cable removal	730,032	240,351	43,250	232,020	1,245,654
Seabed clearance and restoration	318,513	104,865	18,870	101,230	543,480
Total:	3,388,378	1,115,569	200,743	1,076,900	**5,781,591**

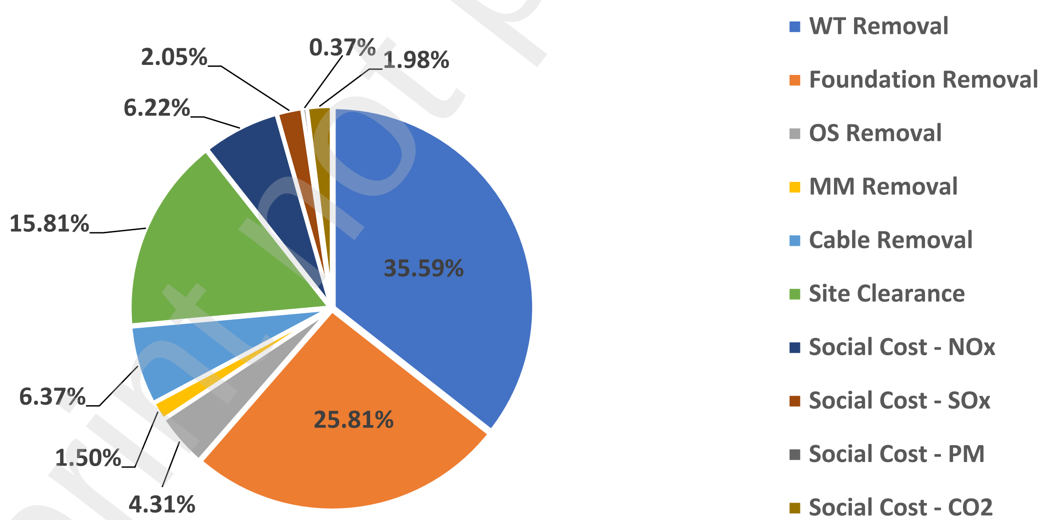


Figure 4. The cost percentage break-down distribution for each activity and pollutant in the Gunfleet Sand case study (minimum scenario)

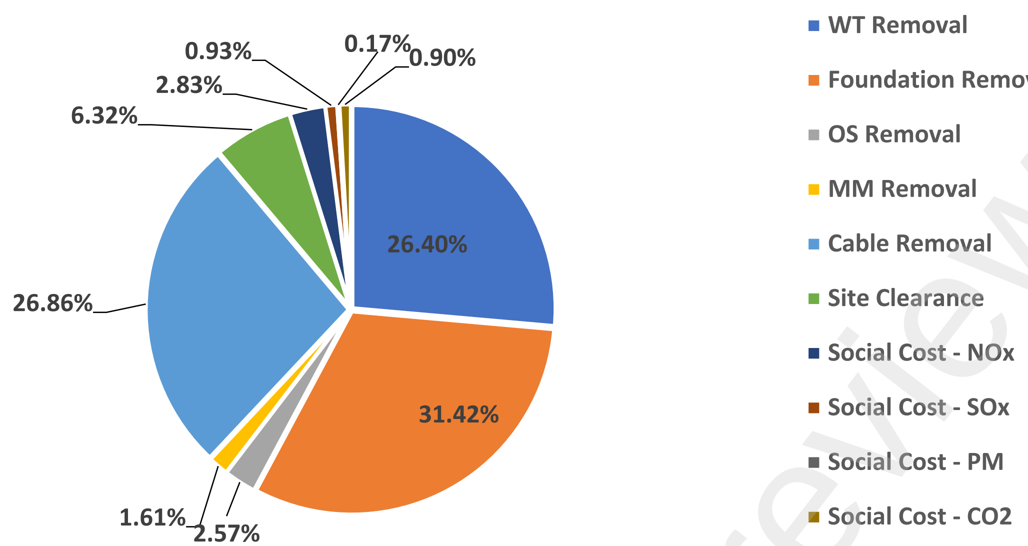


Figure 5. The cost percentage break-down distribution for each activity and pollutant in the Gunfleet Sand case study (maximum scenario)

5.2. Lincs Limited OWF

The second case study investigated is the Lincs Limited OWF shown in Figure 6. This OWF is located 8 km off the coast at Skegness, Lincolnshire, UK. The Lincs Limited includes 75 WTs with 3.6 MW capacities. The overall information on the assets in the Lincs Limited OWF is provided in Table 15. In this OWF, the WTs and OS are supported by steel monopile and jacket structures, respectively. The technical specifications of the foundation structures are listed in Table 16. The DP [21] of the Lincs Limited OWF was predicted 20 years as the operational lifetime. The main intention of this case study is to verify the cost estimation formulations by comparing the results to those predicted in the Linc Limited DP [21].

(a) (b)

Figure 6. The Lincs Limited OWF: (a) location (Google map), (b) site layout [39]

Table 15. Overall information on different assets in Lincs Limited OWF [21]

Specifications	Description
Distance to shore	8 km off the coast at Skegness, Lincolnshire, UK
No. of OS	1
Export cable	132 kV cables with 48 km length
Inter-array cables	33 kV cables with 85 km length
No. of MM	1
Water depth	8 to 18 m
No. of WTs	75×3.6MW
WT type	Siemens Wind Power SWT-3.6
Site area	35 km^2
Scour protection	650 m^3*

*Approximate value assumed in this study

Table 16. Technical specifications of monopile and jacket structures in the Lincs Limited OWF [21]

	Specifications	Description
Monopiles for WTs	Outer shaft diameter	4.7 m - 5 m
	Shaft wall thickness	0.06 m – 0.1 m
	Overall length	36 m – 45 m
	Seabed penetration	27 m – 38 m
	Weight	225-320 tonnes
	Steel	300-700 tonnes
	Concrete	25-100 tonnes for connecting the transition piece
Jacket for OS	Size	20 m × 26 m × 30 m
	Piles	4 leg piles with a diameter of 54"
	Seabed penetration	26 m
	Jacket weight	750-1000 tonnes
	Piles weight	580 tonnes

Although the Lincs DP [21] assumes that the subsea cables and scour protection will be left in their situ, this study assesses the costs and emissions for the complete removal of mentioned assets. The DP [21] provided a set of assumptions on the employed vessels and equipment. It recommends using a single JUV supported by a BV for the WT and foundation removal activities. With this assumption, the JUV will be required to keep waiting during the transportation of dismantled units to the shore, which increases the leasing duration of the JUV. In this study, it is assumed that two BVs will be employed for transportation, one on-site and one in transit. This should minimise the delays in JUV crane operations and so reduce the costs. The DP [21] also assumes that the 9 WT and 10 foundation units will be transported by BV in each transport cycle. No information on the ROV activities was mentioned in the DP [21]. In this study, the ROV costs are also considered in the cost estimations. The assumptions in this study are compared to those described in the Lincs DP [21] in Table 17. The assumed duration and cost parameters for the Lincs Limited case study are listed in Table 18. The assumed values are selected partly based on the information available from the Lincs Limited DP [21] and partly based on the previous experience and available data.

Table 18

Table 17. Comparison of the assumptions considered by the Lincs Limited DP [21] and this study

Asset	Lincs DP [21]	Present study

WTs	• Removal method is considered as the reverse of installation: 1st blade + 2nd blade + 3rd blade + Nacelle + Tower • A JUV was assumed for the WT removal • 1 BV was assumed for transportation • No TBs were mentioned	• The removal method is assumed as the reverse of the installation • A JUV is assumed for the WT removal • 2 BVs and 2 TBs are assumed for transportation
Monopiles and transition pieces	• A JUV was assumed for the foundation removal process • 1 BV was assumed for transportation • No TBs were mentioned • No ROV was mentioned	• Foundations to be cut 1 m below the seabed • Internal cutting is assumed • An OSV is assumed to support the cutting process • A JUV is assumed for the removal process • 2 BVs and 2 TBs are assumed for transportation • An ROV is assumed for subsea operations
OS	N/A	• A JUV is assumed for the OS removal • 1 BV and 1 TB are assumed for transportation • A ROV is assumed for subsea operations
MM	N/A	• A JUV is assumed for the MM removal • 1 BV and 1 TB are assumed for transportation • An ROV is assumed for subsea operations • It is assumed that the removal operation of offshore substation and MM will be performed with the same vessels
Subsea cables	Left in situ	Complete removal
Scour protection	Left in situ	Complete removal

Table 18. Assumed parameter values in the cost and emission estimations for the Lincs Limited case study

	Parameters	Unit	Assumptions		Parameters	Unit	Assumptions
WT removal	$t_{\mathrm{pos}}^{\mathrm{JUV}}$	hr	3[a]	Foundation removal	$t_{\mathrm{pos}}^{\mathrm{OSV}}$	hr	0.25[a]
	$t_{\mathrm{up}}^{\mathrm{JUV}}$	hr	6 [a]		$t_{\mathrm{move}}^{\mathrm{OSV}}$	hr	0.25[a]
	$t_{\mathrm{down}}^{\mathrm{JUV}}$	hr	1[a]		v_{cut}	hr/m	10[a]
	$t_{\mathrm{s}}^{\mathrm{BV}}$	hr	24[b]		Q_{p}	m^3/hr	50[a]
	t_{B}	hr	2[a]		$t_{\mathrm{L,F}}^{\mathrm{JUV}}$	hr	28[a]
	t_{N}	hr	2.5[a]		n_{CF}	units	10[b]
	t_{T}	hr	6[a]		$t_{\mathrm{ol}}^{\mathrm{F}}$	hr/unit	2.4[b]
	n_{CWT}	units	9[b]	Cable removal	L_{I}	km	85[b]
	$t_{\mathrm{WT}}^{\mathrm{ol}}$	hr/unit	12[b]		L_{E}	km	48[b]
	v_{BV}	knots	10		r_{I}	km/day	0.75[c]
OS removal	$t_{\mathrm{c,top}}$	hr	12[d]		r_{E}	km/day	0.80[c]
	$t_{\mathrm{L,top}}$	hr	3[d]		IF_{I}	-	2.25[c]
	$t_{\mathrm{c,p}}$	hr	48[d]		IF_{E}	-	1.50[c]
	$t_{\mathrm{L,j}}$	hr	3[d]	Vessel/ equipment rates	$C_{\mathrm{m}}^{\mathrm{JUV}}$	£	400 k[a]
	$t_{\mathrm{OS}}^{\mathrm{ol,F}}$	hr/unit	3		$C_{\mathrm{D}}^{\mathrm{JUV}}$	£	100 k[a]
	$t_{\mathrm{OS}}^{\mathrm{ol,T}}$	hr/unit	8		$C_{\mathrm{m}}^{\mathrm{BV}}$	£	172.4 k[d]
Seabed clearance and restoration	$t_{\mathrm{pos}}^{\mathrm{DCBV}}$	hr	6[d]		$C_{\mathrm{D}}^{\mathrm{BV}}$	£	12.9 k[a]
	$V_i^{\mathrm{WT}}, V_i^{\mathrm{OS}}, V_i^{\mathrm{MM}}$	m^3	650		$C_{\mathrm{D}}^{\mathrm{TB}}$	£	8.6 k[a]
	r_{ret}	m^3/hr	144[d]		$C_{\mathrm{m}}^{\mathrm{ROV}}$	£	34.48 k[d]
	r_{RD}	Locations/day	8[d]		$C_{\mathrm{D}}^{\mathrm{ROV}}$	£	3.45 k[a]
	$t_{\mathrm{a}}^{\mathrm{DCBV}}$	hr	8[d]		$C_{\mathrm{m}}^{\mathrm{CLV}}$	£	445 k[d]
MM removal	$t_{\mathrm{c,top}}$	hr	4[d]		$C_{\mathrm{D}}^{\mathrm{CLV}}$ (inter-array)	£	69.13 k[c]
	$t_{\mathrm{L,top}}$	hr	3[d]		$C_{\mathrm{D}}^{\mathrm{CLV}}$ (export)	£	59.25 k
	$t_{\mathrm{ol,T}}^{\mathrm{MM}}$	hr/unit	2.4		$C_{\mathrm{m}}^{\mathrm{DCBV}}$	£	100 k[d]
	$t_{\mathrm{ol,F}}^{\mathrm{MM}}$	hr/unit	2.4		$C_{\mathrm{D}}^{\mathrm{DCBV}}$	£	50 k[d]
					$C_{\mathrm{m}}^{\mathrm{RDV}}$	£	10.6 k[d]
					$C_{\mathrm{D}}^{\mathrm{RDV}}$	£	12.5 k[c]

[a]Minimum values were assumed from the available data and experience, [b]Assumed based on Lincs DP [21], [c]Average value was assumed, [d]Only available data was used

Table 19. the removal costs and durations of different decommissioning activities in the Lincs Limited case study

Activity	Source	Total duration (days)	Weather delay (%)	Duration including weather delay (days)	Duration per unit (days/unit)	Removal cost (£)

WT removal	Present study	76.60	20%	91.88	1.23	13,882,925
	Lincs DP [21]	135.00	20%	162.5	2.16	12,184,000
Foundation removal	Present study	160.27 for OSV 37.50 for JUV	20%	192 for OSV 45 for JUV	2.56 for OSV 0.60 for JUV	8,783,084
	Lincs DP [21]	80.00	20%	96.00	1.28	7,498,000*
OS removal	Present study	3.17	20%	3.80	3.80	1,096,510
MM removal	Present study	2.07	20%	2.49	2.49	320,742
Cable removal	Present study	50.37 (inter-array) 40.00 (export)	20%	60.44 (inter-array) 48.00 (export)	0.71 (inter-array) 1.00 (inter-array)	7,876,138
Seabed clearance and restoration	Present study	59.40 (scour protection) 11.55 (rock dumping)	20%	71.28 (scour protection) 13.86 (rock dumping)	120 m^3/hour (scour protection) 6.67 locations/day (rock dumping)	6,212,196 (scour protection) + 169,990 (rock dumping) = 6,382,186
Total cost						**38,341,585**

*Lincs DP [21] predicted £7.2 m for foundation removal plus £298 k for the cutting activities

The emissions produced by the different decommissioning activities in the Lincs Limited case study are listed in Table 20. A major part of the emissions is produced by the WT and foundation removal operations with about 11,000 and 9700 tonnes of CO_2 emissions, respectively. The emissions caused by the transport activities account for about 46% of total produced emissions in the project, which highlights the fact that the transport strategies play an important role in the environmental impact of OWF decommissioning projects. The Lincs DP [21] assumed 0.1 day for the transit duration. Therefore, this study uses the distance of the OWF to the shore for the transit calculations. The decommissioning activities in the Lincs Limited case study are expected to produce about 581, 88, 16, and 30,000 tonnes of NO_x, SO_X, PM, and CO_2 emissions, respectively. Figure 7 shows the CO_2 percentage breakdown distribution, which shows that the WT and foundation removals produce about 36% and 32% of total CO_2 emission in this case study. Moreover, Table 21 lists the social costs caused by the different pollutants for the Lincs Limited case study, which shows an overall social cost of £4.6 m. Figure 8 presents the total cost breakdown distributions for this case study. From Figure 8, the social costs account for about 11% of overall costs, which shows the necessity of considering the social cost in the economic assessment of OWF decommissioning project.

The overall decommissioning costs and emissions can also be represented in terms of £/MW and tonnes/MW of installed capacity, respectively. The overall decommissioning cost for this case study is estimated to be about £160 k/MW. The full seabed clearance and restoration and full cable removal will cost about £53 k/MW with 35 tonnes/MW of CO_2 emissions. The emission analysis turns out that the overall CO_2 emission of decommissioning activities is expected to be about 113 tonnes/MW. The results suggest that the emissions alone cause about £17 k/MW of social costs to the taxpayers and government. However, it should be noted that these values are approximate, and they may vary from one OWF to another one, as the costs and emissions depend on a variety of site-specific information and employed decommissioning strategies.

Table 20. The emissions of different activities for the Lincs Limited case study (tonnes)

Activity		NOx	SO_X	PM	CO_2
WT removal	$E_{\mathrm{WT}}^{\mathrm{tr}}$	153.88	23.21	4.29	8047
	$E_{\mathrm{WT}}^{\mathrm{O}}$	55.15	8.32	1.54	2884
	E_{WT}	209.03	31.53	5.83	10,931
Foundation removal	$E_{\mathrm{F}}^{\mathrm{tr}}$	42.16	6.36	1.18	2205
	$E_{\mathrm{F}}^{\mathrm{O}}$	142.45	21.48	3.97	7449
	E_{F}	184.61	27.84	5.15	9654
OS removal	$E_{\mathrm{OS}}^{\mathrm{tr}}$	2.64	0.40	0.07	137
	$E_{\mathrm{OS}}^{\mathrm{o}}$	2.28	0.34	0.06	119
	E_{OS}	4.90	0.74	0.14	256
MM removal	$E_{\mathrm{MM}}^{\mathrm{tr}}$	1.86	0.28	0.05	97
	$E_{\mathrm{MM}}^{\mathrm{o}}$	1.49	0.23	0.04	78
	E_{MM}	3.35	0.51	0.09	175
Cable removal	E_{C}	71.44	10.78	1.99	3736
Seabed clearance and restoration	$E_{\mathrm{SP}}^{\mathrm{tr}}$	66.79	10.07	1.86	3493
	$E_{\mathrm{SP}}^{\mathrm{O}}$	37.57	5.67	1.05	1965
	E_{SP}	104.35	15.74	2.91	5457
	E_{RD}	3.55	0.54	0.10	186
	E_{SC}	107.90	16.27	3.01	5643
Total transport emissions	$E_{\mathrm{tr}}^{\mathrm{total}}$	267.31	40.32	7.45	13,979
Total operational emissions	$E_{\mathrm{o}}^{\mathrm{total}}$	313.93	47.35	8.75	16,417
Total emissions	E_{total}	**581.24**	**87.66**	**16.20**	**30,396**

Table 21. The social costs caused by the different pollutants in the Lincs Limited case study

Activity	Social costs (£)				
	NOx	SO_X	PM	CO_2	Total
WT removal	976,791	321,593	57,869	310,445	1,666,699
Foundation removal	862,693	284,028	51,110	274,183	1,472,014
Cable removal	333,854	109,916	19,779	106,106	569,655
OS removal	22,905	7,541	1,357	7,279	39,082
MM removal	15,680	5,162	929	4,984	26,755
Seabed clearance and restoration	487,635	160,546	28,890	154,981	860,366
Total social costs	2,716,152	894,250	160,917	863,252	**4,634,571**

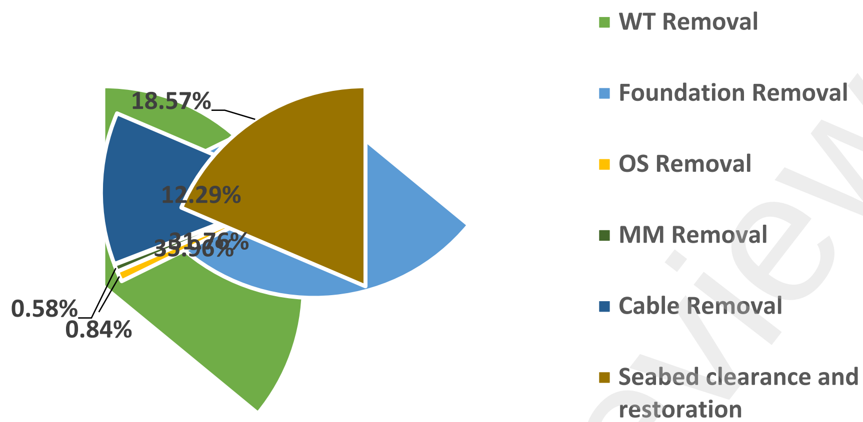


Figure 7. The CO_2 emission percentage break-down distribution for each decommissioning activity in the Lincs Limited case study

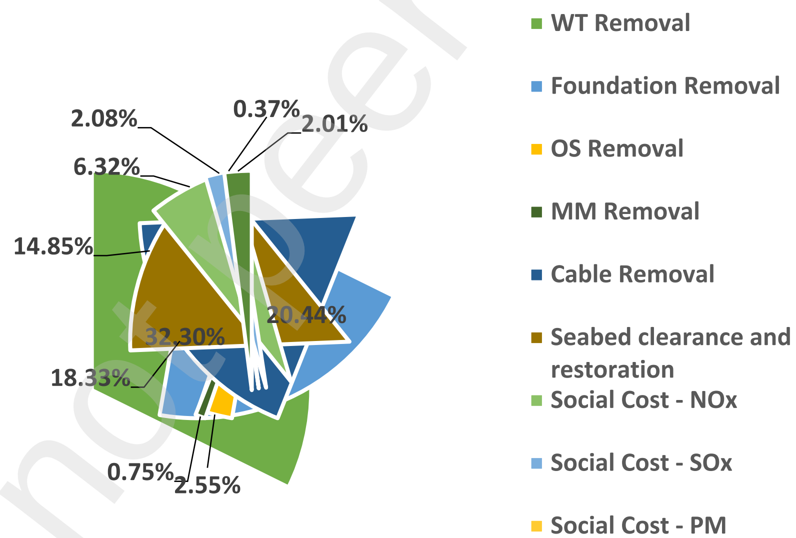


Figure 8. The total removal cost percentage break-down distribution for each decommissioning activity and pollutant in the Lincs Limited case study

5.3. Cost sensitivity analyses

As was discussed in the previous sections, the costs of different decommissioning activities depend on a set of duration and leasing parameters. The main aim of this section is to see how these parameters can affect the overall cost values. To this end, a cost sensitivity analysis of different duration and leasing parameters is performed for the Lincs Limited case study. The different parameter categorises that could affect the cost values of OWF decommissioning activities are listed in Table 22. The overall assumption of the sensitivity analyses in this section is that the changes in the values of different parameters are in the interval of [-90%, 200%].

Table 22. The categorisation of different parameters for decommissioning cost sensitivity analysis

Category	Parameters
Vessel durations	$t_{\mathrm{pos}}^{\mathrm{JUV}}$, $t_{\mathrm{pos}}^{\mathrm{OSV}}$, $t_{\mathrm{pos}}^{\mathrm{DCBV}}$, $t_{\mathrm{down}}^{\mathrm{JUV}}$, $t_{\mathrm{move}}^{\mathrm{OSV}}$, $t_{\mathrm{a}}^{\mathrm{DCBV}}$
Removal durations	t_{B}, t_{T}, t_{N}, $t_{\mathrm{L,F}}^{\mathrm{JUV}}$, r_{I}, r_{E}, $t_{\mathrm{L,top}}$, $t_{\mathrm{L,J}}$, r_{ret}, r_{rd}
Cutting durations	Q_{p}, v_{cut},$t_{\mathrm{c,top}}$, $t_{\mathrm{c,p}}$
Lasing rates	$C_{\mathrm{D}}^{\mathrm{JUV}}$, $C_{\mathrm{D}}^{\mathrm{OSV}}$, $C_{\mathrm{D}}^{\mathrm{BV}}$, $C_{\mathrm{D}}^{\mathrm{CLVi}}$,$C_{\mathrm{D}}^{\mathrm{CLVe}}$, $C_{\mathrm{D}}^{\mathrm{TB}}$, $C_{\mathrm{D}}^{\mathrm{ROV}}$, $C_{\mathrm{D}}^{\mathrm{DCBV}}$, $C_{\mathrm{D}}^{\mathrm{RDV}}$

The results of sensitivity analysis for the vessel duration parameters are illustrated in Figure 9. As can be seen, positioning parameters of JUV and DCBV as well as anchor retrieval of DCBV have the most significant impacts on the overall costs. The reason behind this observation is related to the high leasing rate of these vessels. In contrast, it can be seen from Figure 9 that the changes in the movement parameter of OSV have no significant impact on the cost values.

The variations in the overall cost values due to changes in the removal durations and rates are illustrated in Figure 10. Among the different removal parameters, the removal duration of the blade t_{B} and tower t_{T}, cable removal rates (i.e., r_{I} and r_{E}) and scour protection removal rate r_{ret} have significant impact on the overall cost values. It should be mentioned that the total removal cost is a decreasing nonlinear function of parameters r_{I}, r_{E}, r_{rd}, and r_{ret} involved in the cable removal, site clearance and restoration activities (see sections 2.4 and 2.5), while it is an increasing function for other removal parameters. The parameters involved in the cutting operations are also important parameters which can affect the overall costs as illustrated in Figure 11. From Figure 11, increasing the cutting speed of the foundation can significantly affect the overall cost value. Figure 11 reveals that a 90% increase in cutting speed can reduce the overall cost by about 4%.

The vessel leasing rates are also important parameters that should be properly estimated to predict realistic decommissioning costs. To see how the vessel/equipment costs can make changes in overall cost estimations, Figure 12 demonstrates the sensitivity of the overall cost to the leasing rates. Figure 12 reveals interesting conclusions. It shows the day rate of the JUV has the most remarkable impact on the overall costs. It reveals that the 100% and 200% increases in JUV day rates can result in about 37% and 75% changes in the overall cost values, respectively. The day rate of the BV is also an important parameter. The 100% and 200% changes in BV day rates can cause about 12% and 24% increases in the cost values, respectively, which are still remarkable changes. Similar conclusions can be made for the leasing rates of other equipment/vessels, but with relatively fewer impacts.

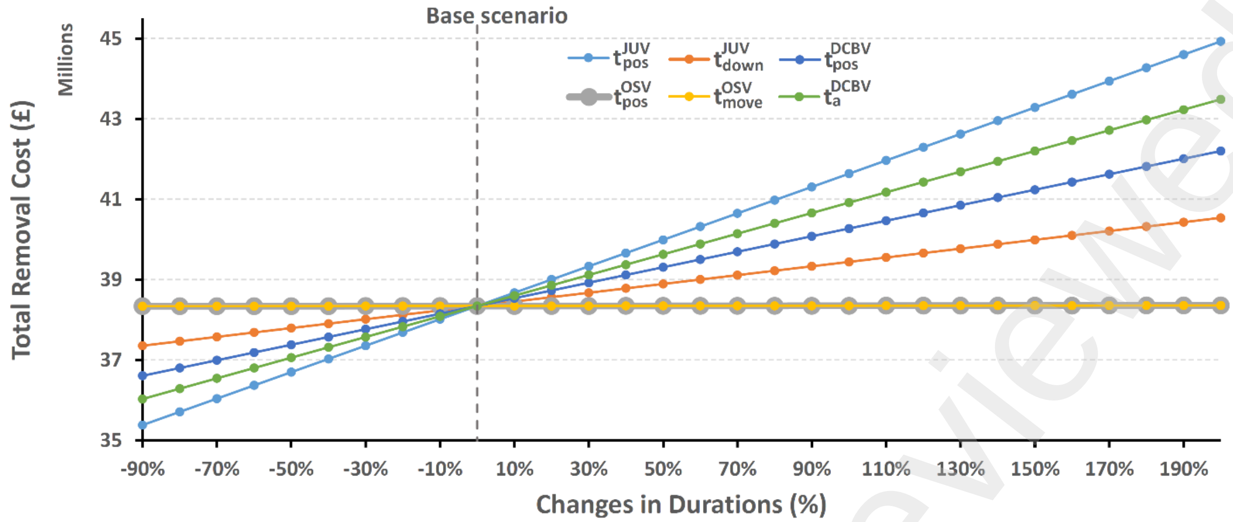


Figure 9. Sensitivity of total removal cost to the vessel duration parameters

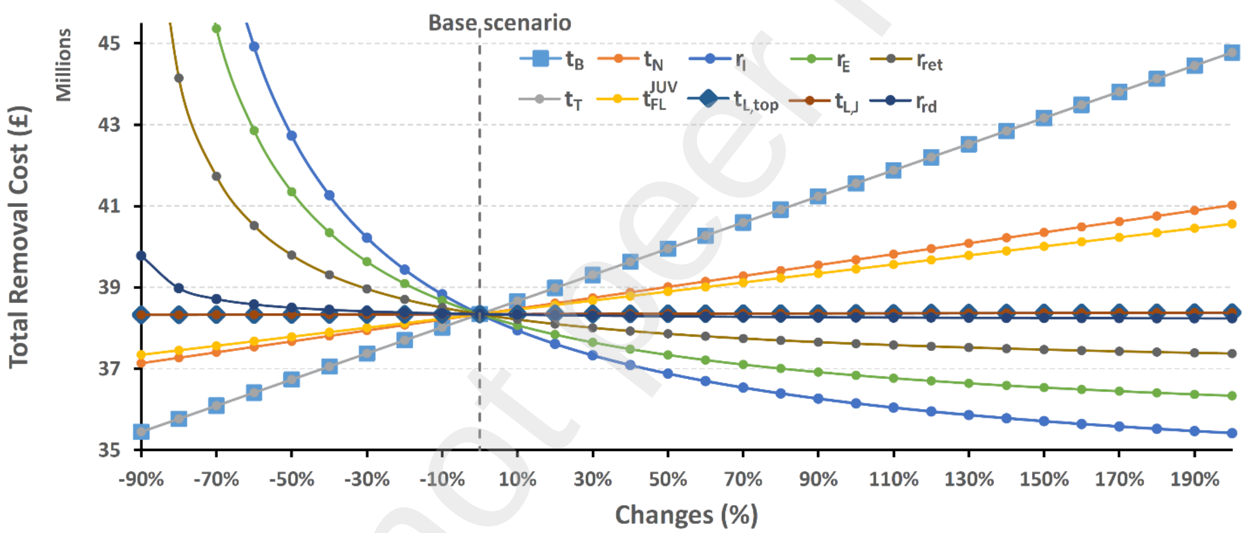


Figure 10. Sensitivity of total removal cost to the removal durations and rates

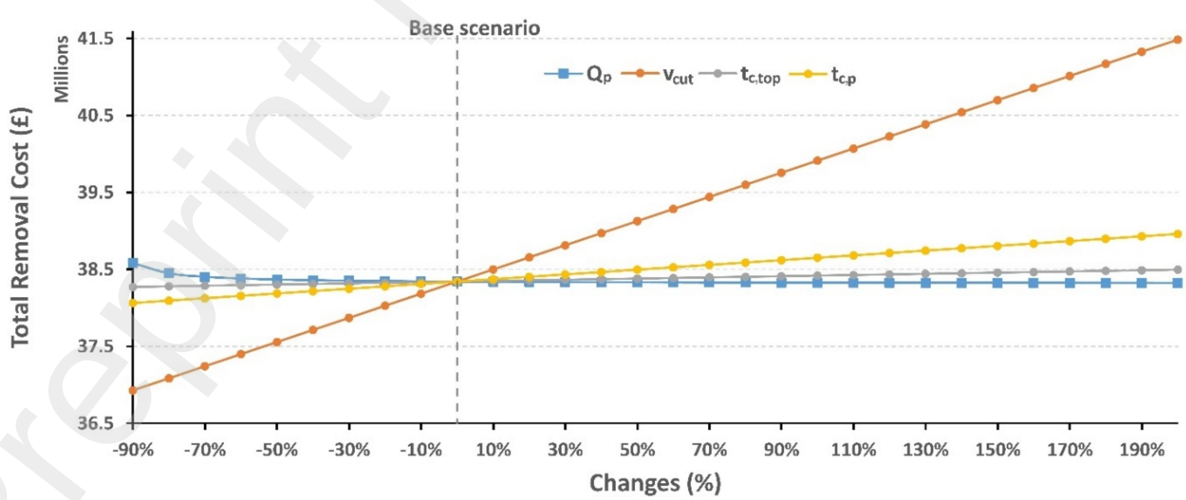


Figure 11. Sensitivity of total removal cost to the parameters involved in the cutting operations

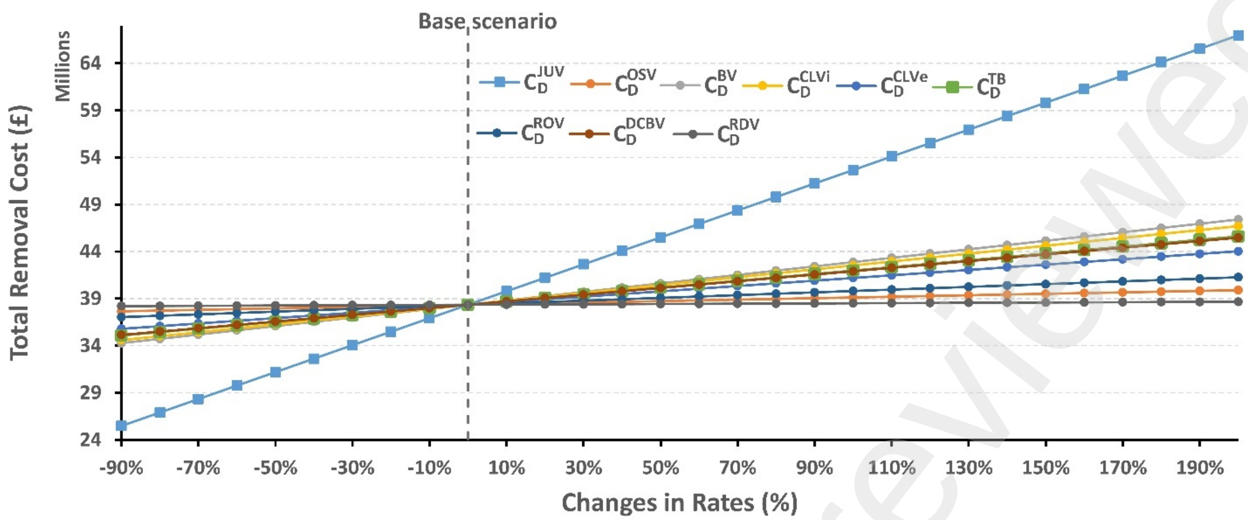


Figure 12. Sensitivity of total removal cost to the vessel/equipment leasing rates

6. Concluding remarks

This study proposes an approach for economic and emissions assessments for OWF decommissioning projects based on a bottom-up model. The detailed formulations are provided for the cost and emission calculations of different decommissioning operations. The proposed formulations include a set of duration and vessels/equipment leasing parameters which may affect the cost and emission estimations. The study gathered available experience and information from different sources to achieve the best possible cost and emission estimations.

To show the effectiveness of the approach, the cost and emission analyses of two real-world OWF case studies in the UK and NSR were investigated, including Gunfleet Sands and Lincs Limited OWFs. In the Lincs Limited case study, the costs and emissions were estimated based on the best possible assumptions for the duration and cost parameters as well as decommissioning strategy. The preciseness of cost estimates for the Lincs Limited case study were investigated through a comparison between the costs obtained by the proposed approach and those reported in the Lincs Limited DP. The results suggested that the proposed approach can estimate the decommissioning costs with an error between 14% and 17% in the cost values. To show how the overall decommissioning cost values can be affected by changes in the different parameter values, a cost sensitivity analysis was performed for the different categories of parameters.

The overall conclusions made from this study can be listed as follows:

- The available experience in the OWF decommissioning is limited, which makes the cost and emissions assessments difficult. The available data gathered from different sources reveal that there are significant uncertainties that can cause inevitable errors in the cost and emission analyses.
- The vessel/equipment leasing rates are subjected to their availability, contract duration, and market situation which can vary depending on the project location. In contrast, the duration parameters depend more on the technology developments and weather conditions.

- This study shows that the social costs caused by the decommissioning projects are not negligible and they should be considered by the policymakers to understand whether the costs and benefits of a proposed policy to curb climate change are justified. The results suggested that the social costs of the projects can vary between 5% and 11%. The results also showed that the emissions alone can cause about £17 k/MW of social costs to the taxpayers and government.
- The study highlighted the importance of transport strategies in the emission analysis of OWF decommissioning projects, accounting about 46% of total emissions of the project.
- The study reflected the fact that the full removal operations of subsea cables and scour protection materials are relatively expensive activities with large amounts of emissions. The percentage break-down analyses suggested that the contributions of these activities to the overall cost and CO_2 emission are about 33% and 31%, respectively. The full seabed clearance and restoration and full cable removal will cost about £53 k/MW with 35 tonnes/MW of CO_2 emissions.
- The cost sensitivity analysis results show that the leasing and duration parameters of the JUV have a significant impact on the overall cost values. Shorter tower and blade removal durations could also significantly reduce the overall removal costs. Foundation cutting speed is also another important parameter which highlights the necessity of future developments in cutting techniques.

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