Interreg
North Sea Region
Decom Tools
European Regional Development Fund

EUROPEAN UNION

Cost and Emission Analyses of Decommissioning of Offshore Wind Farms Using Reverse Installation Method: Cases of Lincs Limited, Gunfleet Sands, and Horns Rev I Wind Farms

DECOMTOOLS 2022

Project Acronym:	**DecomTools**
Reference Number:	**Interreg North Sea Region– Project Number: 20180305091606**
Project Title:	**Eco-Innovative concepts for the end of offshore wind energy farms lifecycle**
Authors:	**Shahin Jalili (University of Aberdeen)**
	Alireza Maheri (University of Aberdeen)
	Ana Ivanovic (University of Aberdeen)

Project Partners:

Abbreviations

BV	Barge Vessel
CLV	Cable Laying Vessel
DCBV	Derrick Crane Barge Vessel
DP	Decommissioning Programme
IEA	International Energy Agency
MM	Meteorological Mast
OS	Offshore Substation
OSV	Offshore Support Vessel
OWF	Offshore Wind Farm
IF	Inflation Factor
JUV	Jack-Up Vessel
ROV	Remotely Operated Vehicle
RDV	Rock Dumping Vessel
TB	Tug Boat
WT	Wind Turbine

Contents

1 Introduction

During the last decade, different international protocols, such as Kyoto [1] or Paris Agreement [2], and the European 2030 climate & energy framework [3], have been developed to deal with the global warming challenge and reduce its impact on the planet. According to the International Energy Agency (IEA) [4], the energy sector is the major contributor to global greenhouse gas emissions with 13.6 billion tons of CO2, accounting for 41% of total emissions in 2018. Renewable energies play a key role in the international roadmaps towards the global net-zero goal. Offshore wind energy is one of the important green renewable energy sources that can significantly contribute to the emission reduction efforts in the energy sector.

Nowadays, urgent climate change action has intensified the investments in the development of Offshore Wind Farms (OWFs) to deal with the greenhouse gas emission reduction challenge. The European Union (EU) with a total capacity of 18.52 GW in 2018 is the global leader in the offshore wind industry. Recently announced roadmaps reveal that the EU countries are determined to keep the global leadership and boost the offshore wind capacity to 150 GW and 460 GW in 2030 and 2050, respectively [5-7]. Although the development of offshore wind can significantly reduce the emissions in the energy sector, there are serious concerns about the environmental and economic impacts of OWF projects. The available experience from the previously constructed OWFs suggests that their operational lifetime does not last long, expected to be between 20 and 25 years [8,9].

One of the possible options for the end of the lifetime of OWFs is repowering or re-utilisation. However, based on the current knowledge and practice, the repowering or re-utilisation of OWF assets is not often economically justifiable or technically straightforward and complete dismantling is needed. In some cases, the decommissioning of OWFs can even take place earlier than expected. For example, Yttre Stengrund OWF [10] needed to be decommissioned after 15 years and the assets of Utgrunden OWF [11] dismantled after 18 years of operation. The majority of the previously constructed OWFs should be eventually decommissioned in the coming years which can potentially cause unwanted disruption of the seabed and marine life as well as significant unexpected costs and emissions. Hence, the need for the development of sustainable technical approaches and realistic policies for the end of the lifetime of OWFs is vital to reduce the potential environmental impacts and costs.

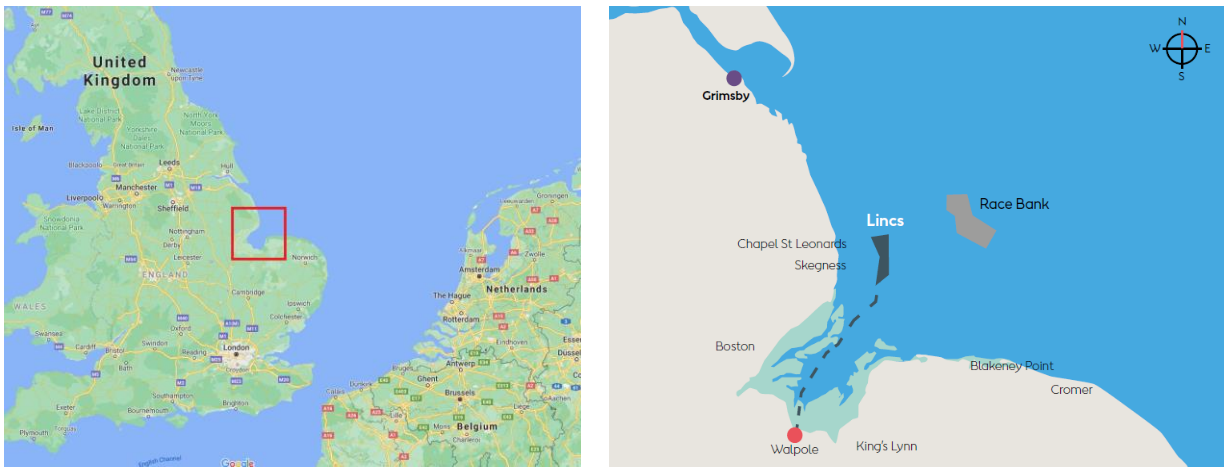
The importance of OWF decommissioning projects intensified the efforts for the development of regulations in this newly emerging field. As the global leader country in offshore wind energy, the UK government has published a set of regulations for OWF decommissioning projects. The guidance [12] published by the UK government under the Energy Act 2004 provides a set of useful information to assist the businesses in the wind industry in understanding their obligations in decommissioning OWF installations. Recently, the Scottish government has also published its guidance on decommissioning projects in offshore renewable energy [13]. Alongside these regulations, the OWF developers should also consider other related regulations, such as those in environmental protection and nature preservation. However, the regulations for OWF decommissioning in most countries are still in the development stage and new regulations or additional changes are expected in a near future. All these efforts highlight the fact that the OWF decommissioning is a real challenge on the horizon of European countries and should be properly addressed by involved parties.

A holistic assessment of OWF decommissioning projects requires comprehensive cost and environmental impact analyses to facilitate the decision-making process for the developers and policymakers. Decommissioning is still new for OWF owners/developers that demands efficient decisions to minimise the costs and possible impacts on the environment. However, the prediction of costs and emissions for the OWF decommissioning projects is not an easy task due to the limited technical experience of the industry and the lack of available data. In this report, the cost and emission analyses of OWF decommissioning projects are addressed based on a bottom-up approach. The report tries to develop efficient cost and emission analyses based on the available data and experience. To show the challenge of data absence, a set of future OWF decommissioning case studies are investigated in terms of the costs and emissions. The case studies are Lincs Limited and Gunfleet Sands OWFs in the UK and Horn Rev I OWF in Denmark. In the investigated case studies, the costs and emissions for the different removal activities, including Wind Turbine (WT) removal, foundation removal, Offshore Substation (OS) removal, Meteorological Mast (MM) removal, cable removal, scour protection removal, site restoration, and transportation are calculated based on the site-specific and logistic information.

The rest of this report is organised as follows. Section 2 investigates the Lincs Limited OWF case study and the comparisons of the results between the current study and the available Decommissioning Programme (DP) for this OWF. In Section 3, the Gunfleet Sands OWF is investigated to show the uncertainties in cost and emission calculations based on the available data and experience. Section 4 discusses the detailed cost and emission results for the Horn Rev I OWF. Finally, the summary and concluding remarks will be presented in Section 5. The results in this report are obtained based on the cost and emission formulations presented in Appendixes A and B. The emission factors and the assumed social costs are also provided in Appendixes C and D.

2 Lincs Limited OWF

The Lincs Limited shown in Fig. 1 is an OWF consisting of 75 WTs located 8 km off the coast at Skegness, Lincolnshire, UK. Its construction process was started in April 2010 and continued until August 2012. The Lincs Limited OWF was officially inaugurated in August 2013. This OWF can generate the required electrical energy for about 240,000 homes in the UK. Table 1 lists the general information about the different assets in the Lincs Limited OWF. The foundations of WTs are monopile structures, whereas the foundation of the offshore substation is a jacket structure. Table 2 presents the technical information for different foundations in the Lincs Limited OWF. The DP [14] of the Lincs Limited OWF assumed 20 years of design life for this wind farm.



(a) (b)

Fig. 1. The Lincs Limited OWF: (a) Regional location (Google map), (b) Site layout [15]

Table 1. The data for the Lincs Limited OWF

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

Table 2. The specifications for the foundations in Lincs Limited OWF [14]

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

Based on the DP of the Lincs Limited OWF [14], the export and inter-array cables as well as scour protections will be left in their situation. For the removal of WTs, the DP assumes one JUV for lifting operations and one BV for transportation. It also states that the WT and foundation removal operations will be performed over separate stages. In each cycle of the WT removal operations, 8 WTs will be transported by the BVs to the shore. Hence, the JUV would need to wait until the BV returns to the site after unloading the dismantled parts. Fig. 2 shows the delay caused by the transportation phase which increases the rental duration of the JUV. The DP [14] assumes a similar strategy for the foundation removal, but it considers that 8 foundations will be removed and transported to shore in each stage. However, a single JUV alongside two BVs are considered in this report, one on the site and one in transit. The Lincs DP [14] does not show any ROV in its cost estimations. We assume that an ROV is also utilised to support the inspection and cutting processes of the foundations.

Table 3 compares the decommissioning strategies assumed by the DP [14] and this report. It is assumed that the scour protection, as well as both the inter-array and export cables, will be left in their situation. The Lincs DP [14] does not show the cost estimations for the OS removal operation. In this report, the cost estimation will be calculated for the OS based on previous experience. Moreover, we assume two TBs are used for towing the BVs. It should be noted that the DP [14] applies the WT removal Method I explained in Appendix A.1. For the foundation removal, it is assumed in this report that Method II discussed in Appendix A.2 will be applied, in which a JUV and an OSV are assumed to support lifting and cutting activities.

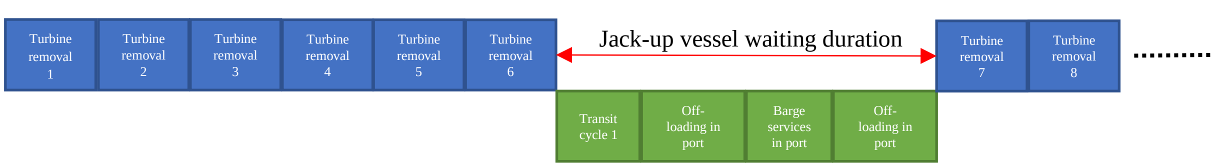


Fig. 2. Example sequence of removal operations for the Lincs Limited OWF

Table 3. The decommissioning strategies for the Lincs Limited OWF

Asset	Decommissioning strategy	Applied vessels/equipment	
		Lincs DP [14]	This report
WTs	- Complete removal - Reverse installation - Removal method II : 1^{st} blade + 2^{nd} blade + 3^{rd} blade + Nacelle + Tower	- A JUV was assumed for the turbine removal process - 1 BV was assumed for transportation - No TBs were mentioned	- A JUV is assumed for the turbine removal process - 2 BV are assumed for transportation - 2 TBs
Monopiles and transition pieces	- To be cut 1 m below the seabed, Intern - Internal cutting for monopile removal	- A JUV was assumed for the foundation removal process - 1 BV was assumed for transportation - No TBs were mentioned - No ROV was mentioned	- An OSV is assumed to support the cutting process - A JUV is assumed for the removal process - 1 BV is assumed for transportation - A ROV for underwater operations - 1 TBs
OS	Complete removal	N/A	- A JUV is assumed for the removal process - 1 BV is assumed for transportation - A ROV for underwater operations - 1 TB
MM	Complete removal	N/A	- A JUV is assumed for the removal process - 1 BV is assumed for transportation - A ROV for underwater operations - 1 TB - It is assumed that the removal operation of offshore substation and MM will be performed with the same vessels
Subsea cables	Left in situ.	Left in situ.	Left in situ.
Scour protection	Left in situ.	Left in situ.	Left in situ.

Table 4 lists the parameters assumed in this report to calculate the removal costs for the Lincs Limited OWF. For all duration parameters, the possible minimum values are selected from the available data explained in the previous sections. Moreover, the mobilisation/demobilisation and day rates of the different vessels/equipment employed for the removal operations are listed in Table 5. The rates are selected from minimum values among the available rates from the past.

Table 4. Assumed parameter values in cost estimations for the Lincs Limited OWF

Removal Operation	Vessel types	Description	Unit	Assumed values	Comment(s)
Wind farm parameters	d_{port}	Distance the wind farm site from the port	km	8	
	n_{t}	No. of turbines		75	
	n_{OS}	No. of offshore substations		1	
Vessel parameters	$t_{\mathrm{pos}}^{\mathrm{JUV}}$	Positioning duration of JUV	hr	3	Minimum was assumed
	$t_{\mathrm{up}}^{\mathrm{JUV}}$	Jacking-up duration of JUV	hr	6	Minimum was assumed
	$t_{\mathrm{down}}^{\mathrm{JUV}}$	Jacking-down duration of JUV	hr	1	Minimum was assumed
	$t_{\mathrm{pos}}^{\mathrm{OSV}}$	Positioning duration of OSV	hr	0.25	Minimum was assumed
	$t_{\mathrm{move}}^{\mathrm{OSV}}$	Movement duration of OSV	hr	0.25	Minimum was assumed
WT removal	t_{B}	Removal duration of a single blade	hr	2	Minimum was assumed
	t_{N}	Removal duration of the nacelle	hr	2.5	Minimum was assumed
	t_{T}	Removal duration of the whole tower section	hr	6	
	No. of JUVs			1	
	No. of BVs			2	One on the site and one in transportation are assumed in this report
	No. of TBs			2	Assumed in this report
Foundation removal	v_{cut}	Cutting speed of the monopile	hr /m	10	Maximum speed was assumed
	Q_{pump}	Pumping rate of the mud inside the monopile	m^3/hr	50	Maximum was assumed
	$t_{\mathrm{L}}^{\mathrm{JUV}}$	Lifting duration of the foundation	hr	2	Minimum was assumed
	No. of JUVs			1	
	No. of BVs			1	
	No. of TBs			1	
	No. of ROVs			1	
OS removal	$t_{\mathrm{c,top}}$	Cutting duration of the OS topside	hr	12	
	$t_{\mathrm{L,top}}$	Lifting duration of the OS topside	hr	3	
	$t_{\mathrm{c,p}}$	Cutting durations of jacket piles	hr	48	
	$t_{\mathrm{L,j}}$	Lifting duration of the jacket structure	hr	3	
	No. of JUVs			1	
	No. of BVs			1	
	No. of TBs			1	
	No. of ROVs			1	

Table 5. The vessel types and their rates assumed for the Lincs Limited OWF

Removal Operation	Vessel types	Quantity	Assumed rates (£)	
			Mobilisation/ Demobilisation	Day rate
WT removal	JUVs	1	400 k	100 k
	BVs	2	172.4 k	12.9 k
	TBs	2	-	8.6 k
Foundation removal	JUV	1	400 k	100 k
	OSV	1	-	3.9 k
	BVs	2	172.4 k	12.9 k
	TB	2	-	8.6 k
	ROV	1	34.48 k	3.45 k
OS removal	JUV	1	400 k	100 k
	BV	1	172.4 k	12.9 k
	TBs	1	-	8.6 k
	ROV	1	34.48 k	3.45 k
MM removal	JUV	1	400 k	100 k
	BV	1	172.4 k	12.9 k
	ROV	1	34.48 k	3.45 k

Table 6 compares the removal costs obtained from the formulations presented in this report to those reported in Lincs DP [14]. From this table, it can be seen that the removal durations for WTs and foundations obtained in this report are shorter than those mentioned in the Lincs DP. The main reason for this difference stems from the fact that the different transportation strategy was adapted by the Lincs DP, in which the JUVs must wait until the BV returns to the site. The DP [14] assumes 20% for the weather delays. From Table 6, it can be observed that the total WT removal duration obtained in this report is about 92 days, while the corresponding duration reported in Lincs DP [14] is about 163 days. The Lincs DP [14] assumes a single JUV for the foundation removal. However, by considering the OSV with significantly cheaper rates in this report, the duration of the JUV is dramatically reduced. It can be seen that the foundation removal duration using JUV reported by Lincs DP [14] is 96 days, while the same duration obtained in this report is about 60 days. Regarding the removal costs, it can be seen from Table 6 that the WT and foundation removal costs obtained in this report are about £13.88m and £9.49m, respectively, while the corresponding values calculated by the Lincs DP [14] are about £12.2m and £7.2m, respectively. There may be several reasons behind the differences in the removal cost values. The first possible reason is the difference in the transportation strategy adopted by this report and the Lincs DP [14], which can potentially affect the costs. In addition, the removal costs calculated by the Lincs DP [14] are based on 2009 rates which can be another reason for the cost differences. The vessel rates can significantly affect the removal cost values. Moreover, this report considered the costs related to the ROVs and TBs, which are not mentioned/considered by the Lincs DP. The differences between the estimated costs are about 14% and 31% for the WT and foundation removals, respectively. Furthermore, this report calculated the removal duration of 3.8 days with a cost of about £1.1m for the OS removal.

Table 7 lists the emissions of different pollutants resulting from different removal operations in the Lincs Limited OWF. From this table, it can be seen that the total CO_2 emission resulting from WT, foundation, and OS removal operations are about 9,000, 10,800, and 260 tons, respectively. The overall CO2 emission resulting from the WT, foundation, and OS removal operations in this case study is about 18,600 tons. Table 8 lists the social costs of generated emissions in the project, which shows an additional cost of £2.8m for the project.

Table 6. The costs and durations of different removal operations for the Lincs Limited OWF

Activity		Total duration (days)	Weather delay (%)	Duration including weather delay (days)	Duration per unit (days/unit)	Removal cost (£)
WT removal	This report	76.6	20%	91.88	1.23	13,882,925
	Lincs DP [1]	135	20%	162.5	2.16	12,184,000
Foundation removal	This report	160.27 for OSV 49.78 for JUV	20%	192 for OSV 59.75 for JUV	2.56 for OSV 0.77 for JUV	9,485,643
	Lincs DP [1]	80	20%	96	1.28	7,200,000
OS removal	This report	3.17	20%	3.80	3.80	1,096,510

Table 7. The emissions of different removal operations for the Lincs Limited OWF (ton)

Activity		NOx	SOx	PM	CO_2
WT removal	$E_{\mathrm{tr}}^{\mathrm{WT}}$	116.81	17.62	3.26	6,108.60
	E_{o}^{WT}	55.15	8.32	1.54	2,883.92
	E_{WT}	171.96	25.93	4.79	8,992.53
Foundation removal	$E_{\mathrm{tr}}^{\mathrm{F}}$	27.99	4.22	0.78	1,463.72
	$E_{\mathrm{o}}^{\mathrm{F}}$	151.30	22.822	4.22	7,912.25
	E_{F}	179.29	27.04	5.00	9,376
OS removal	$E_{\mathrm{tr}}^{\mathrm{OS}}$	2.64	0.40	0.07	138.27
	$E_{\mathrm{o}}^{\mathrm{OS}}$	2.28	0.34	0.06	119.28
	E_{OS}	4.92	0.74	0.14	257.55
Total		356.17	53.72	9.93	18,626

Table 8. The social costs related to the different pollutants in the Lincs Limited OWF

Activity	Social costs (£)				
	NOx	SOx	PM	CO_2	Total
WT removal	803,557	264,558	47,606	255,388	1,371,109
Foundation removal	837,820	275,839	49,636	266,277	1,429,573
OS removal	23,014	7,577	1,363	7,314	39,269
Total	1,664,391	547,975	98,606	528,980	2,839,951

3 Gunfleet Sands OWF

Gunfleet Sands OWF is located 8.5 km off the southeast coast of Clacton-on-Sea, Essex, UK. This OWF was commissioned in three different phases. Fig. 3 illustrates the regional location and general site layout of the Gunfleet Sands OWF, at which the first and second phases consist of 30 and 18 WTs, respectively.

(a) (b)

Fig. 3. The Gunfleet Sands OWF: (a) Regional location (Google map), (b) Site layout [16]

The third phase of Gunfleet Sands OWF is a demonstration project consisting of two 6 MW turbines. Fig. 4 illustrates the cable layout in this OWF. With a total capacity of 185 MW, this OWF can generate electricity for over 160,000 UK homes. The first and second phases of the Gunfleet Sands OWF were officially inaugurated in June 2010 and the third phase was installed in September 2013. The life span of this OWF is designed for a minimum of 20 years [17]. The general data related to the Gunfleet Sands OWF are presented in Table 9.

All of the foundations in this OWF are monopile structures. The technical specifications for the monopile structures are presented in Table 10. In this report, the first two phases will be considered for numerical investigations. The environmental statement [18] for the Gunfleet Sands OWF published in 2007 briefly predicted some decommissioning activities. Table 11 lists the decommissioning strategy assumed in this report for the Gunfleet Sands OWF. Some of the contents of this table were obtained from Refs. [18,19], while some assumptions are considered based on the installation reports of this OWF.

Table 9. The data for the Gunfleet Sands OWF

	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 [17]
	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 [18]
Phase I (GS-I)	No. of WTs	30×3.6MW
	WTs spacing	435×890 m [18]
	WT type	Siemens Wind Power SWT-3.6-107
	Site area	10 km^2 [18]
Phase II (GS-II)	No. of WTs	18×3.6MW
	WTs spacing	435×890 m [18]
	WT type	Siemens Wind Power SWT-3.6-107
	Site area	7.5 km^2 [18]

Table 10. The monopile foundation specifications for the Gunfleet Sands OWF [17]

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

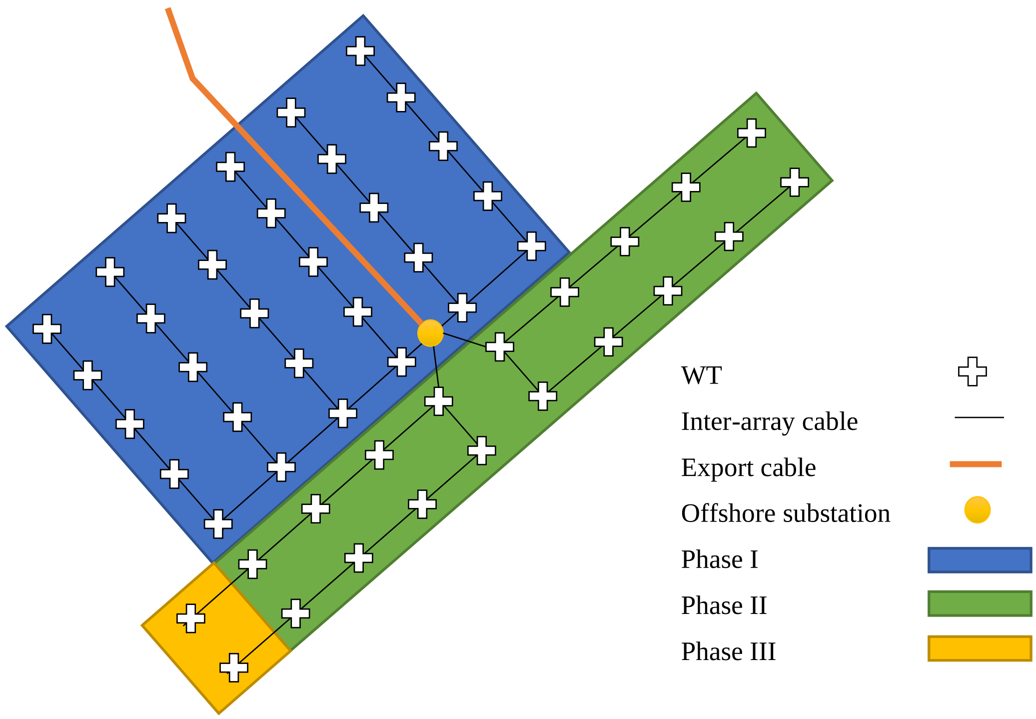


Fig. 4. The locations of WTs and the cable layout in the Gunfleet Sands OWF

The removal cost estimations are highly sensitive to the uncertainties in different parameters. In this case study, the minimum and maximum values for each of the parameters are considered to calculate the possible upper and lower bound estimations. Table 12 lists the minimum and maximum values assumed for the parameters in this case study. In addition, Table 13 presents the minimum and maximum mobilisation/demobilisation costs and day rates for the different types of vessels\equipment employed in the removal operations. All upper and lower bounds listed in Tables 12 and 13 are selected based on the available data in the OWF decommissioning literature [20]. In the cost calculations, two scenarios are considered. In the first scenario, it is assumed that all of the removal operations are performed in the cheapest way with minimum possible duration and delays. The second scenario is a pessimistic scenario that assumes all of the removal operations are performed by assuming maximum possible costs with the longest duration and delays. These two scenarios can provide a general picture of how the removal costs can be affected by these parameters.

Table 11. The decommissioning strategy for the Gunfleet Sands OWF (information was gathered from Ref. [18,19])

Asset	Installation techniques and equipment	The decommissioning strategy adopted in this report
WTs	- Jack-up barge - Installation method: Tower+Nacelle+Blade+Blade+Blade	- Reverse installation - A JUV and two BVs are assumed for WT removal
Monopiles and transition pieces	- The installation of the monopiles and transition pieces was performed by the crane barge in deeper water and the jack-up barge in shallower water	- Internal cutting for monopile removal - High-pressure water/grit cutting tool will be used - The mud inside the monopile needs to be pumped up to 1 m below the cutting line - The cutting line was not specified - It is assumed in this report that the foundation will be cut from 1 m below the seabed - It is assumed in this report that one OSV will be used to support cutting operations of the foundation - A JUV is assumed for foundation liftings - It is assumed in this report that one barge will be used for transportation
OS	-	- A JUV is assumed for lifting and a BV is considered for the transportation
Subsea cables	- A cable installation vessel was used	- The intention is to remove only uncovered parts of the cables - Survey will be performed - Exposed cable ends where a foundation has been removed will be buried - It is assumed a CLV and an ROV will be required - Two scenarios are considered in this report: 1. Left in situation 2. Total removal
Scour protection	-	- Two scenarios are considered in this report: 1. Left in situation 2. Total removal
Rock dumping	-	- A rock dumping vessel is assumed for the foundation locations

Table 12. Assumed parameter values in cost estimations for the Gunfleet Sands OWF.

Removal Operation	Vessel types	Description	Unit	Assumed values	
				Min	Max
Wind farm parameters	d_{port}	Distance the wind farm site from the port	km	8.5	8.5
	n_{t}	No. of turbines		48	48
	n_{OS}	No. of OSs		1	1
Vessel parameters	$t_{\mathrm{pos}}^{\mathrm{JUV}}$	Positioning duration of JUV	hr	3	8
	$t_{\mathrm{up}}^{\mathrm{JUV}}$	Jacking-up duration of JUV	hr	6	9
	$t_{\mathrm{down}}^{\mathrm{JUV}}$	Jacking-down duration of JUV	hr	1	4
	$t_{\mathrm{pos}}^{\mathrm{OSV}}$	Positioning duration of OSV	hr	0.25	2
	$t_{\mathrm{move}}^{\mathrm{OSV}}$	Movement duration of OSV	hr	0.25	2
WT removal	t_{B}	Removal duration of a single blade	hr	2	3.33
	t_{N}	Removal duration of the nacelle	hr	2.5	6
	t_{T}	Removal duration of the whole tower section	hr	6	6
	No. of JUVs			1	1
	No. of BVs			2	2
	No. of TBs			2	2
	n_{cycle}	No. of foundations for transportation in each cycle		2	5
Foundation removal	v_{BV}	Towing speed of BVs	knots	5	10
	d_{c}	Cutting depth of the foundation under the seabed	m	1	1
	e	Space provided for the ease of access to the cutting line	m	1	2
	v_{cut}	Cutting speed of the monopile	hr/m	10	24
	Q_{pump}	Pumping rate of the mud inside the monopile	m^3/hr	25	50
	$t_{\mathrm{L}}^{\mathrm{JUV}}$	Lifting duration of the foundation	hr	2	8
	No. of JUVs			1	1
	No. of BVs			1	1
	No. of TBs			1	1
	No. of ROVs			1	1
	n_{cycle}	No. of foundations for transportation in each cycle		5	10
Cable removal	L_{I}	Inter-array cable length	km	34	34
	L_{E}	Export cable length	km	9	9
	r_{I}	Installation rate for inter-array cables	km/day	0.15	0.60
	r_{E}	Installation rate for export cables	km/day	0.20	1.40
	IF_{I}	Inflation factor for the inter-array cables		1.5	3.0
	IF_{E}	Inflation factor for the export cables		1.0	2.0
OS removal	$t_{\mathrm{c,top}}$	Cutting duration of the OS topside	hr	12	12
	$t_{\mathrm{L,top}}$	Lifting duration of the OS topside	hr	3	3
	No. of JUVs			1	1
	No. of BVs			1	1
	No. of TBs			1	1
	No. of ROVs			1	1
MM removal	$t_{\mathrm{c,top}}$	Cutting duration of the MM topside	hr	4	4
	$t_{\mathrm{L,top}}$	Lifting duration of the topside	hr	3	3
	$t_{\mathrm{c,p}}$	Cutting durations of the foundation	hr	36	36
	No. of JUVs			1	1
	No. of BVs			1	1
	No. of TBs			1	1
	No. of ROVs			1	1
Seabed clearance and restoration	$V_i^{\mathrm{WT}}, V_i^{\mathrm{OS}}, V_i^{\mathrm{MM}}$	Scour protection material volume around the *i*th WT, OS, and MM, respectively	m^3	575	575
	r_{ret}	The removal rate of scour protection materials	m^3/hr	144	144
	r_{rd}	Rock dumping rate	Locations/day	8	8
	$t_{\mathrm{pos}}^{\mathrm{DCBV}}$	Positioning duration of the derrick crane BV to start the removal operation	hr	6	6
	$t_{\mathrm{a}}^{\mathrm{DCBV}}$	The time required by the derrick crane BV to retrieve its anchors	hr	8	8

Table 13. The vessel/equipment types and their rates assumed for the Gunfleet Sands OWF

Removal Operation	Vessel types	Quantity	Mobilisation/Demobilisation (£)		Day rate	
			Minimum	Maximum	Minimum	Maximum
WT removal	JUVs	1	400 k	445 k	100 k	200 k
	BVs	2	172.4 k	172.4 k	12.9 k	30 k
	TBs	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
	BVs	2	172.4 k	172.4 k	12.9 k	30 k
	TB	2	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
	TBs	1	N/A	N/A	8.6 k	19.4 k

The minimum and maximum expected removal costs alongside the removal durations calculated based on the available data are presented in Table 14. Like the previous case study, it is assumed that the weather delay is about 20%. From this table, it can be seen that the minimum and maximum removal durations for the WTs are about 1.22 days/turbine and 2.15 days/turbine. The minimum turbine removal cost is estimated to be about £9.1m, while the maximum expected cost is about £31.6m. Although the removal duration is increased less than two times, the removal cost soared more than three times. The remarkable increase in the removal costs is related to the mobilisation/demobilisation and day rates assumed for the second scenario. For example, from Table 13, it can be seen the day rate of the JUV, BV, and TV in two cost scenarios are significantly different which can almost double the overall cost values for the vessels/equipment. This shows how the vessel rates and the market situation can affect the decommissioning costs. Similar conclusions can be made for the costs related to the other removal operations. Fig. 5 compares the removal costs obtained from the minimum and maximum cost scenarios, in which it can be seen the cost differences are more significant for WT, foundation, and cable removal operations. It should be noted that since only single data is available for the site clearance and restoration, the costs obtained for both scenarios are the same.

Table 14. The costs and durations calculated for different removal operations in the Gunfleet Sands OWF

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) 31.70 (JUV)	20%	123.08 (OSV) 38.03 (JUV)	2.56 (OSV) 0.79 (JUV)	6,263,338
	Maximum	251.14 (OSV) 65.88 (JUV)	20%	301.37 (OSV) 79.06 (JUV)	6.28 (OSV) 1.65 (JUV)	36,761,683
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

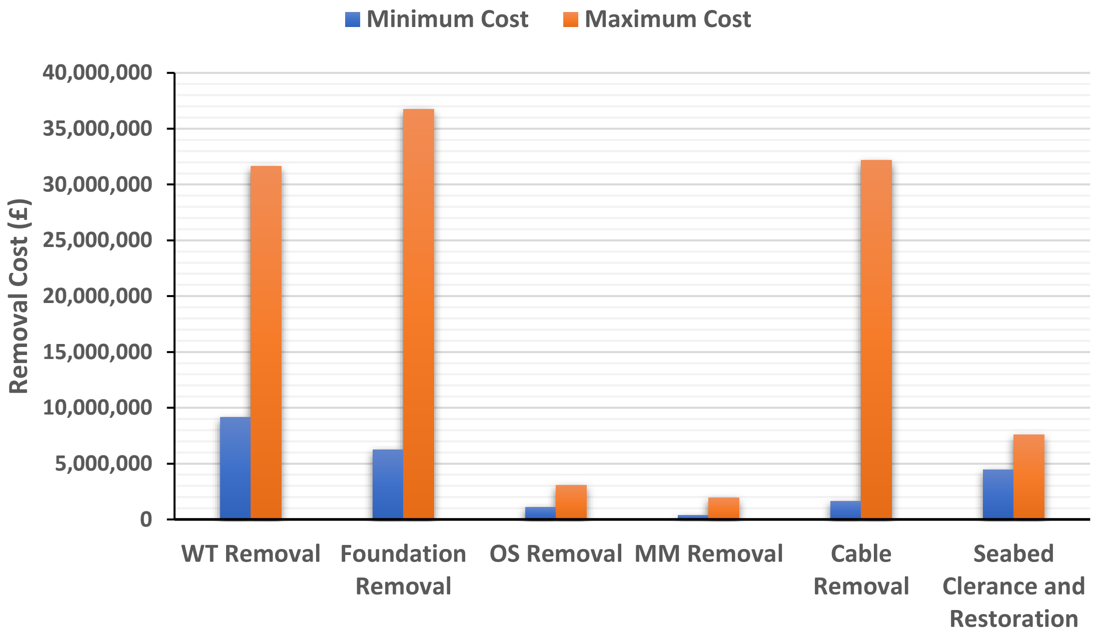


Fig. 5. The removal cost comparisons between the minimum and maximum cost scenarios in Gunfleet Sands OWF

The emissions resulting from each removal operation for the minimum and maximum cost scenarios are presented in Tables 15 and 16, respectively. The related emissions formulations are also presented in Appendix B. Figs. 6 and 7 also show the percentage breakdown distribution of the CO_2 emissions related to each removal operation. As it can be seen from these figures, the WT removal operation is the major contributor to the CO_2 emissions in the minimum cost scenario, while the CO2 emission from the foundation removal operation is greater than all others in the maximum cost scenario. Moreover, Tables 17 and 18 list the social costs resulting from different pollutants for different activities.

Figs. 8 and 9 graphically compare the social costs resulting from each activity for each cost scenario, in which it can be seen that NOx, SOx, and CO2 are major contributors to the social costs. The total decommissioning costs should be evaluated by considering the social costs resulting from the pollutants. The total removal cost percentage break-down distributions for each removal operation and pollutant are shown in Figs. 10 and 11. From these figures, it can be seen that about 10% up to 12% of total removal costs are related to the social costs resulting from the different pollutants.

Table 15. The emissions of different removal operations in the minimum cost scenario for the Gunfleet Sands OWF (ton)

Activity	Emissions	NOx	SOx	PM	CO_2
WT removal	$E_{\mathrm{tr}}^{\mathrm{WT}}$	89.26	13.46	2.49	4,667.87
	E_{o}^{WT}	35.29	5.32	0.98	1,845.71
	E_{WT}	124.55	18.79	3.47	6,513.58
Foundation removal	$E_{\mathrm{tr}}^{\mathrm{F}}$	17.82	2.69	0.50	931.69
	$E_{\mathrm{o}}^{\mathrm{F}}$	96.71	14.59	2.70	5,057.32
	E_{F}	114.52	17.27	3.19	5,989
OS removal	$E_{\mathrm{tr}}^{\mathrm{OS}}$	2.69	0.40	0.08	140.52
	$E_{\mathrm{o}}^{\mathrm{OS}}$	2.33	0.35	0.07	122.08
	E_{OS}	5.02	0.76	0.14	262.60
MM removal	$E_{\mathrm{tr}}^{\mathrm{MM}}$	2.27	0.34	0.06	118.42
	$E_{\mathrm{o}}^{\mathrm{MM}}$	1.79	0.27	0.05	93.77
	E_{MM}	4.06	0.61	0.11	212.19
Cable removal	E_{C}	17.56	2.65	0.49	918.23
Seabed clearance and restoration	$E_{\mathrm{tr}}^{\mathrm{SP}}$	42.15	6.36	1.18	2,204.07
	$E_{\mathrm{o}}^{\mathrm{SP}}$	23.71	3.58	0.66	1,239.79
	E_{SP}	65.86	9.93	1.84	3,443.87
	E_{RD}	2.31	0.35	0.06	120.58
	E_{SC}	68.17	10.28	1.90	3,564
Total:		333.88	50.36	9.31	17,460

Table 16. The emissions of different removal operations in the maximum cost scenario for the Gunfleet Sands OWF (ton)

Activity	Emissions	NOx	SOx	PM	CO_2
WT removal	$E_{\mathrm{tr}}^{\mathrm{WT}}$	179.72	27.11	5.01	9,398.5
	E_{o}^{WT}	61.93	9.34	1.73	3,238.65
	E_{WT}	241.65	36.45	6.74	12,637.12
Foundation removal	$E_{\mathrm{tr}}^{\mathrm{F}}$	37.04	5.59	1.03	1,936.9
	$E_{\mathrm{o}}^{\mathrm{F}}$	228.35	34.44	6.36	11,941.5
	E_{F}	265.39	40.03	7.40	13,878.4
OS removal	$E_{\mathrm{tr}}^{\mathrm{OS}}$	4.77	0.72	0.13	249.20
	$E_{\mathrm{o}}^{\mathrm{OS}}$	4.97	0.75	0.14	259.86
	E_{OS}	9.73	1.47	0.27	509.06
MM removal	$E_{\mathrm{tr}}^{\mathrm{MM}}$	3.97	0.60	0.11	207.44
	$E_{\mathrm{o}}^{\mathrm{MM}}$	3.95	0.60	0.11	206.36
	E_{MM}	7.91	1.19	0.22	413.81
Cable removal	E_{C}	156.22	23.56	4.35	8,169.72
Seabed clearance and restoration	$E_{\mathrm{tr}}^{\mathrm{SP}}$	42.15	6.36	1.18	2,204.07
	$E_{\mathrm{o}}^{\mathrm{SP}}$	23.71	3.58	0.66	1,239.79
	E_{SP}	65.86	9.93	1.84	3,443.87
	E_{RD}	2.31	0.35	0.06	120.58
	E_{SC}	68.17	10.28	1.90	3,564
Total:		749.07	112.97	20.88	39,173

Table 17. The social costs related to the different pollutants for the minimum cost scenario in the Gunfleet Sands OWF

Activity	Social costs (£)				
	NOx	SOx	PM	CO_2	Total
WT removal	582,042	191,628	34,482	184,985	993,139
Foundation removal	535,168	176,196	31,706	170,088	913,157
OS removal	23,466	7,725	1,390	7,458	40,040
MM removal	18,960	6,242	1,123	6,026	32,352
Cable removal	82,051	27,014	4,861	26,077	140,004
Seabed clearance and restoration	318,513	104,865	18,870	101,230	543,479
Total:	1,560,202	513,672	92,433	495,866	**2,662,172**

Table 18. The social costs related to the different pollutants for the maximum cost scenario in the Gunfleet Sands OWF

Activity	Social costs (£)				
	NOx	SOx	PM	CO_2	Total
WT removal	1,129,231	371,781	66,900	358,894	1,926,808
Foundation removal	1,240,150	408,300	73,472	394,146	2,116,068
OS removal	45,488	14,976	2,694	14,457	77,617
MM removal	36,977	12,174	2,190	11,752	63,094
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:	3,500,392	1,152,449	207,379	1,112,500	**5,972,720**

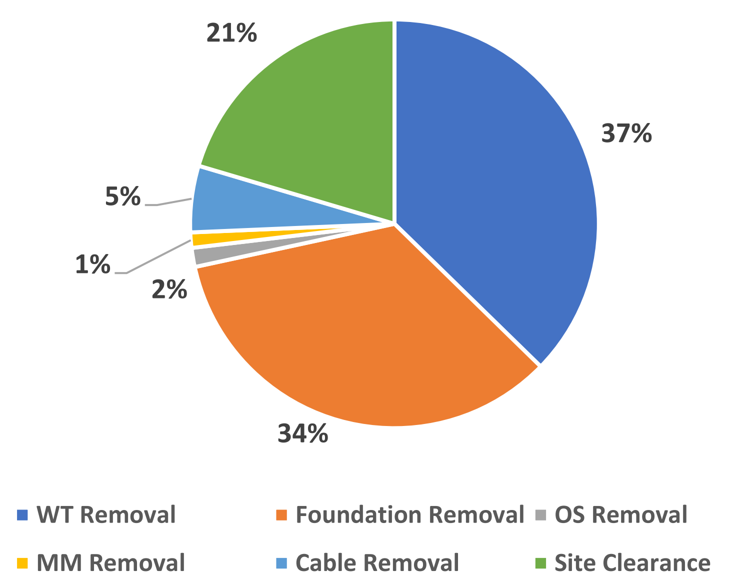


Fig. 6. The CO_2 emission percentage break-down distribution for each removal operation in Gunfleet Sand OWF (minimum scenario)

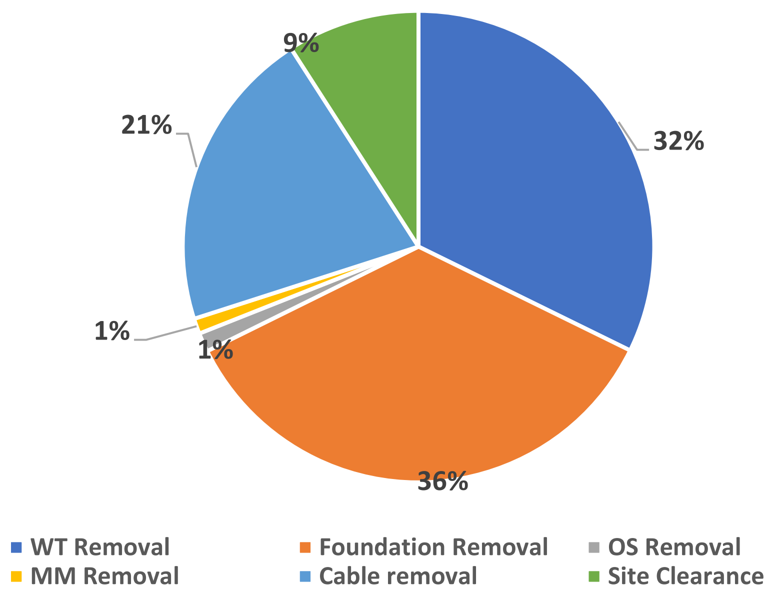


Fig. 7. The CO_2 emission percentage break-down distribution for each removal operation in Gunfleet Sand OWF (maximum scenario)

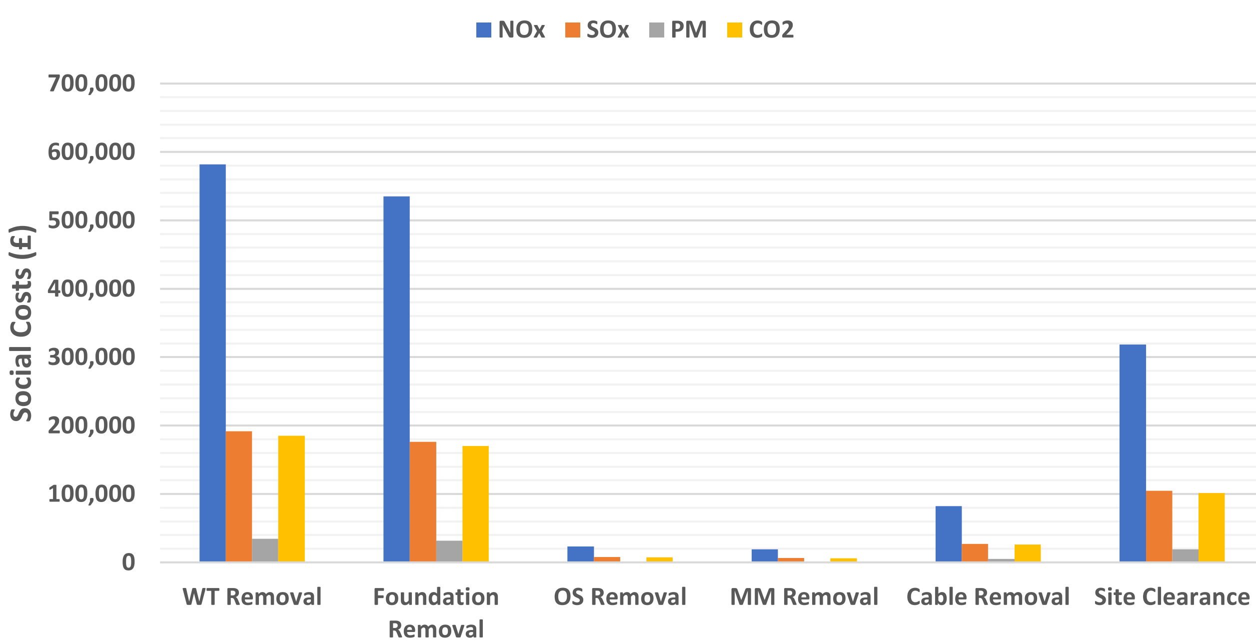


Fig. 8. The social costs of different pollutants resulted from different activities in Gunfleet Sand OWF (minimum scenario)

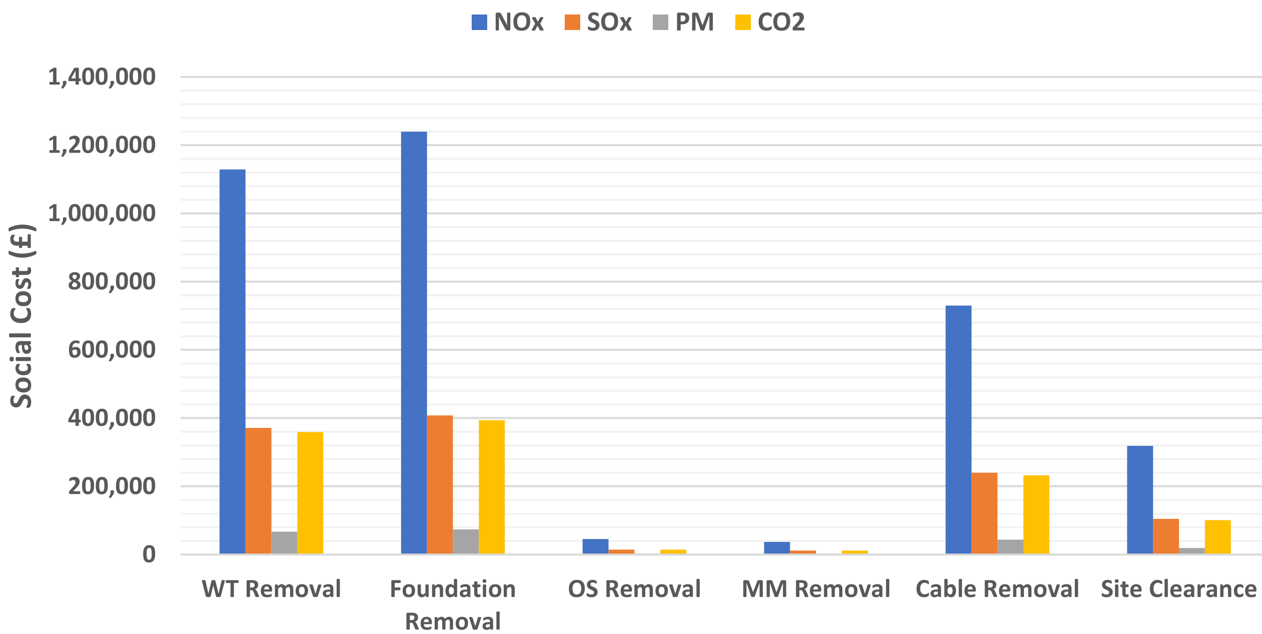


Fig.9. The social costs of different pollutants resulted from different activities in Gunfleet Sand OWF (maximum scenario)

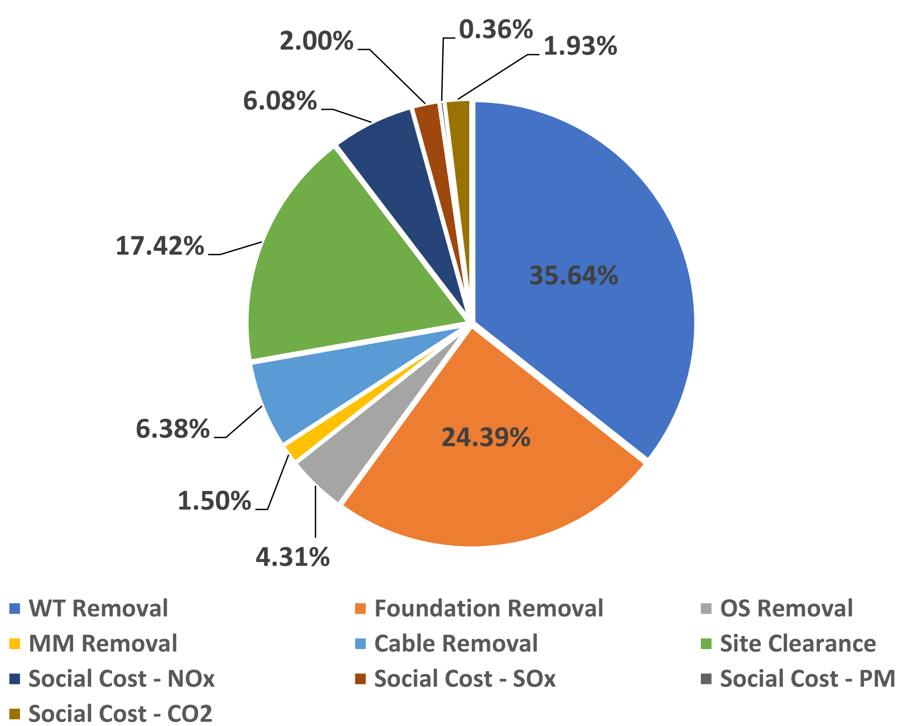


Fig. 10. The total removal cost percentage break-down distribution for each removal operation and pollutant in Gunfleet Sand OWF (minimum scenario)

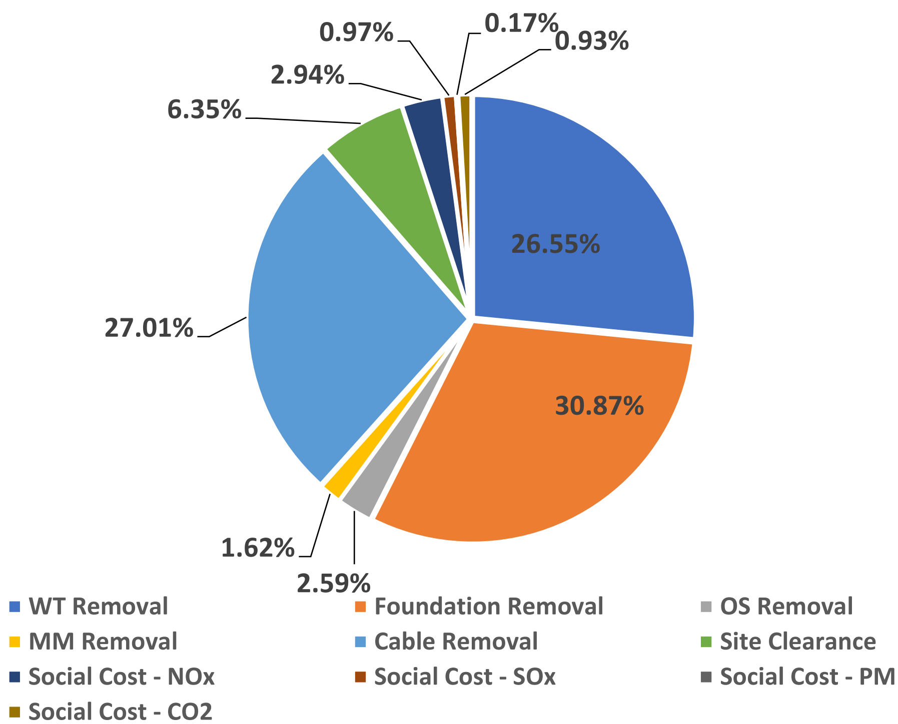


Fig. 11. The total cost percentage break-down distribution for each removal operation and pollutant in Gunfleet Sand OWF (maximum scenario)

4 Horns Rev I

Horns Rev is an OWF located on the west coast of Denmark. The first phase of this OWF, called Horns Rev I, was commissioned in 2002. The OWF generates 2% of Denmark's total electricity demand [21]. The OWF consists of 80 Vestas V80 WTs with a capacity of 2 MW per turbine, which resulted in a total capacity of 160 MW. Fig. 12 and Fig. 13 illustrate the geographical location of Horns Rev I OWF and its layout and export cable path. The distance between the WTs is about 560 m. A total scour protection with an area of 50,000 m^2 was designed to cover the seabed around the offshore foundations. The WT and OS foundations are monopile structures with a diameter of about 4 m. The inter-array cables connect the WTs with a total length of 64 km. The OS is connected to the shore with an export cable of 21 km in length. The foundation of OS in this case study consists of five monopiles, which can make the removal process costly and time-consuming.

Table 19 lists the general information about the different assets in Horns Rev I OWF. The areas around the monopile foundations on the seabed in Horns Rev OWF are protected to prevent erosion. The scour protection consists of two protective layers, including a stone mattress and a gravel mattress. The first layer is a gravel layer of 0.5 m in width which is consisted of small stones with diameters between 0.03 up to 0.2 m. The gravel layer is protected by a stone layer of 0.8 m in width consisting of large stones up to 0.55 m in diameter. The scour protection design in Horns

Rev 1 OWF is illustrated in Fig. 14. By assuming the circle with a diameter of 25 m, the total scours protection volume can be approximately calculated.

Fig. 12. The geographical location and layout of Horns Rev I OWF in Denmark [22]

Table 19. The data for the Horns Rev I OWF [22-27]

Specifications	Description
Distance to shore	15 km
No. of OSs	1
Export cable	150 kV with a total length of 21 km
Inter-array cables	36 kV with a total length of 64 km
Burial depth of cables	2 m
No. of MMs	1
Water depth	Between 6.5 m to 13.5 m
Scour protection	• Total approximate scour protection area of monopiles: 40,000 m^2 • Scour protection layer thickness: 1.3 m • Scour protection layer diameter: 25 m
No. of WTs	80
WTs spacing	560 m
WT type	Vestas V80-2.0
Site area	24 km^2
Monopile diameter	3.4 m to 4.0 m
Monopile Sea bed penetration	25 m

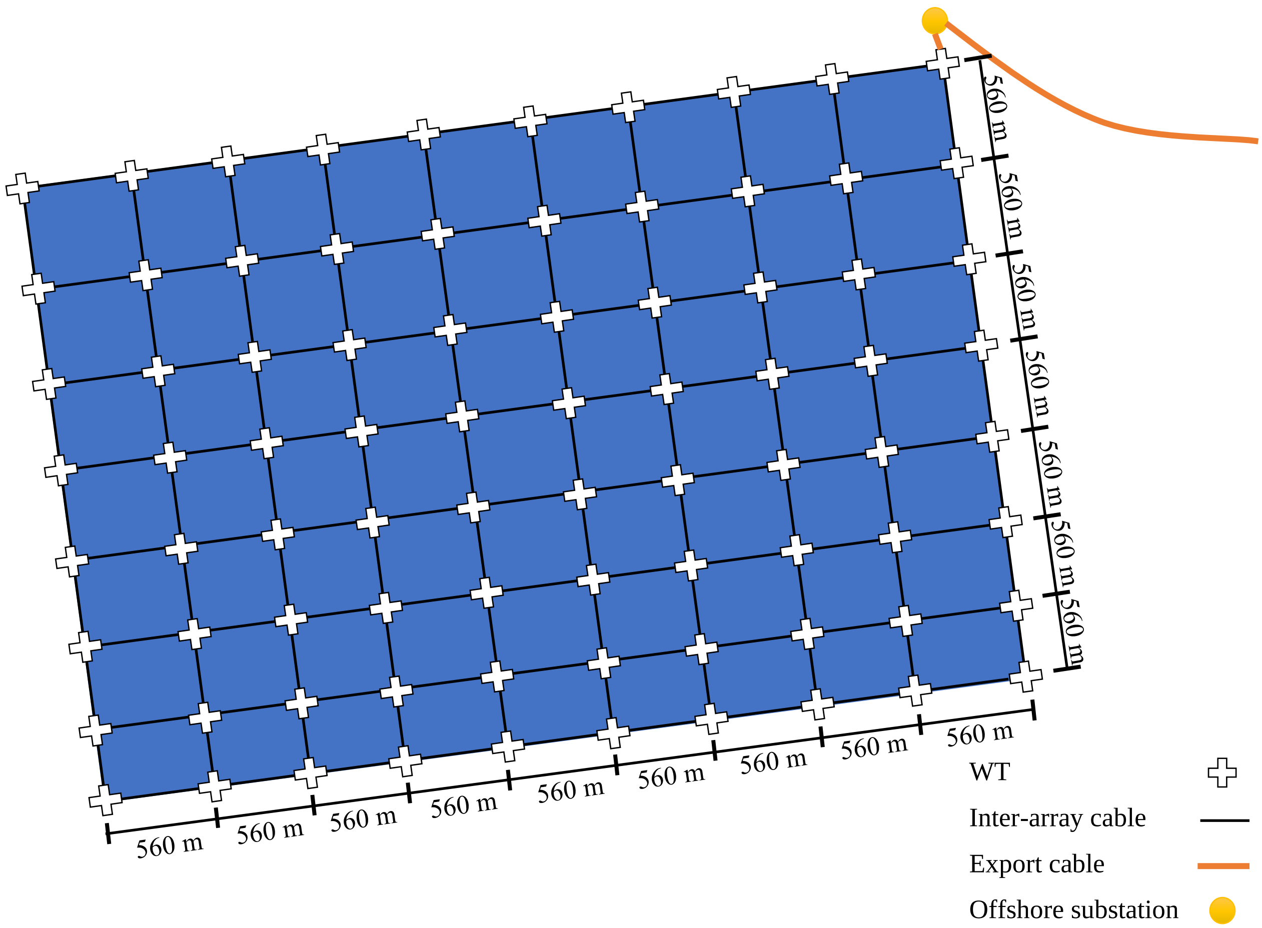


Fig. 13. The locations of WTs and the cable layout in Horns Rev I OWF

In the installation of Horns Rev I OWF, the WTs were installed based on the bunny-ear configuration, i.e., Method V explained in Appendix A.1. Based on [28], two JUVs, including Sea Power and Sea Energy, were used for WT installation. The foundation installation was performed by a JUV and a BV. The OS was also installed by using JUV and BV. In this case study, it is assumed that similar strategies will be used for the decommissioning operations. Table 20 presents the comparison between the decommissioning strategy assumed in this report and the installation strategy of Horns Rev I OWF. The WT units will be dismantled based on the Method V described in Appendix A.1. The foundation removal will be performed using a single JUV and based on the Method I explained in Appendix A.2.1. It is also assumed that the cables and scour protection will be removed in the decommissioning stage. Table 21 lists the assumed values for the cost parameters in this case study. The values are the estimations made based on the available information for this OWF. The assumed mobilisation/demobilisation costs and day rates for the vessels/equipment employed in this case study are listed in Table 22.

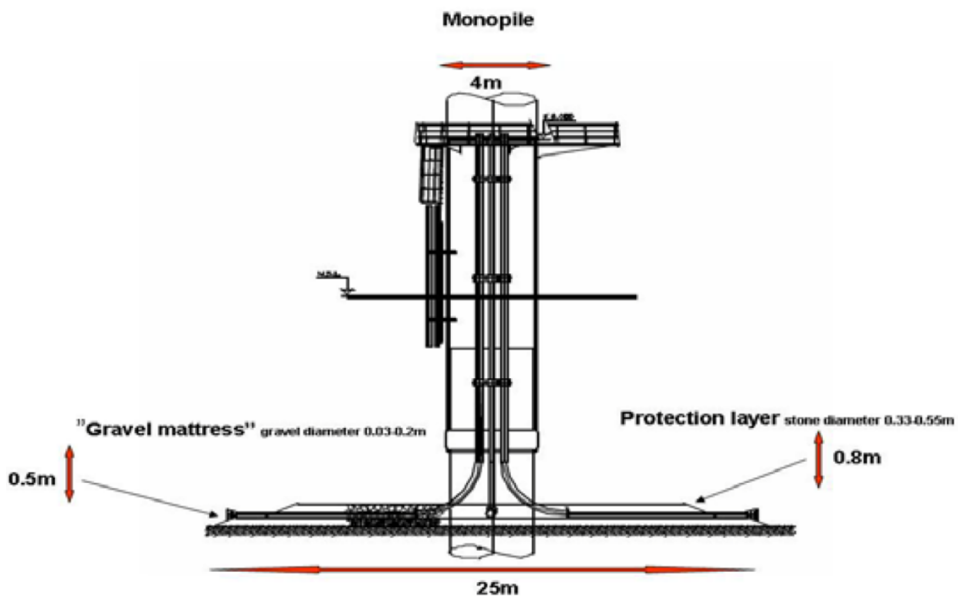


Fig. 14. Scour protection around the monopile foundations in Horns Rev OWF [27]

Table 20. Assumed decommissioning strategy for Horns Rev I OWF (information was gathered from Refs. [25,28])

Asset	Installation techniques/equipment/vessels	The decommissioning strategy adopted in this report
WTs	- Self-propelled JUVs: Sea Energy (JUV) + Sea Power (JUV) - Installation method: Method V, Tower+(Nacelle+2Blades)+Blade	- Reverse installation - Two JUVs are considered for WT removal - No BVs are needed
Monopiles and transition pieces	- Buzzard (jack-up barge vessel) - BV	- A JUV is assumed for foundation liftings - It is assumed in this report that one BV will be used for transportation
OS	- Buzzard (jack-up barge vessel) - BV - Installed on 5 monopiles	- A single JUV for lifting processes - A single BV is assumed for OS transportation
MM	N/A	- A single JUV for lifting processes - A single BV is assumed for MM transportation
Subsea cables	- C.S. Sovereign- cable installation and maintenance vessel provided by Global Marine - C.S. Sovereign vessel was used for both inter-array and export cables installations	- An CLV is assumed for both inter-array and export cables.
Scour protection	-	- A DCBV is assumed. - A single BV is assumed for transportation.
Rock dumping	-	- A rock dumping vessel is assumed for the foundation locations.

Table 21. Assumed parameter values in cost estimations for Horns Rev I OWF

Removal Operation	Vessel types	Description	Unit	Assumed values
Wind farm parameters	d_{port}	Distance the wind farm site from the port	km	23
	n_{t}	No. of turbines		80
	n_{OS}	No. of OSs		1
Vessel parameters	$t_{\mathrm{pos}}^{\mathrm{JUV}}$	Positioning duration of JUV	hr	8
	$t_{\mathrm{up}}^{\mathrm{JUV}}$	Jacking-up duration of JUV	hr	9
	$t_{\mathrm{down}}^{\mathrm{JUV}}$	Jacking-down duration of JUV	hr	1
WT removal	t_{B}	Removal duration of a single blade	hr	6
	$t_{\mathrm{N+R+2B}}$	Removal duration of the nacelle and two blades (bunny ear)	hr	12
	t_{T}	Removal duration of the whole tower section	hr	10
	No. of JUVs			2
	No. of BVs			-
	No. of TBs			3
	n_{cycle}	No. of foundations for transportation in each cycle		2
	v_{JUV}	Sailing speed of JUV	knots	8
Foundation removal	v_{BV}	Towing speed of BVs	knots	8
	d_{c}	Cutting depth of the foundation under the seabed	m	1
	e	Space provided for the ease of access to the cutting line	m	1
	v_{cut}	Cutting speed of the monopile	hr/m	10
	Q_{pump}	Pumping rate of the mud inside the monopile	m^3/hr	50
	$t_{\mathrm{L}}^{\mathrm{JUV}}$	Lifting duration of the foundation	hr	2
	No. of JUVs			1
	No. of BVs			1
	No. of TBs			1
	No. of ROVs			1
	n_{cycle}	No. of foundations for transportation in each cycle		10
Cable removal	L_{I}	Inter-array cable length	km	64
	L_{E}	Export cable length	km	21
	r_{I}	Installation rate for inter-array cables	km/day	0.33
	r_{E}	Installation rate for export cables	km/day	1.25
	IF_{I}	Inflation factor for the inter-array cables		3
	IF_{E}	Inflation factor for the export cables		2
OS removal	$t_{\mathrm{c,top}}$	Cutting duration of the OS topside	hr	12
	$t_{\mathrm{L,top}}$	Lifting duration of the OS topside	hr	3
	No. of JUVs			1
	No. of BVs			1
	No. of TBs			1
	No. of ROVs			1
MM removal	$t_{\mathrm{c,top}}$	Cutting duration of the MM topside	hr	4
	$t_{\mathrm{L,top}}$	Lifting duration of the topside	hr	3
	No. of JUVs			1
	No. of BVs			1
	No. of TBs			1
	No. of ROVs			1
Seabed clearance and restoration	$V_i^{\mathrm{WT}}, V_i^{\mathrm{OS}}, V_i^{\mathrm{MM}}$	Scour protection material volume around the *i*th WT, OS, and MM, respectively	m^3	615
	r_{ret}	The removal rate of scour protection materials	m^3/hr	144
	r_{rd}	Rock dumping rate	Locations/day	8
	$t_{\mathrm{pos}}^{\mathrm{DCBV}}$	Positioning duration of the derrick crane BV to start the removal operation	hr	6
	$t_{\mathrm{a}}^{\mathrm{DCBV}}$	The time required by the derrick crane BV to retrieve its anchors	hr	8

Table 22. The vessel\equipment types and their rates assumed for Horns Rev I OWF

Removal Operation	Vessel types	Quantity	Mobilisation/Demobilisation (£)	Day rate
WT removal	JUV	2	400 k	178 k
Foundation removal	JUV	1	400 k	200 k
	BV	1	172.4 k	44 k
	TB	2	N/A	8.6 k
	ROV	1	34.48 k	3.45 k
OS and MM removals	JUV	1	400 k	178 k
	BV	1	172.4 k	44 k
	TBs	2	N/A	8.6 k
	ROV	1	34.48 k	3.45 k
Cable removal	CLV (inter)	1	445 k	134 k
	CLV (export)	1	445 k	134 k
	ROV	1	34.48 k	3.45 k
Seabed clearance and restoration	DCBV	1	100 k	50 k
	RDV	1	10.6 k	11.9 k
	BV	1	172.4 k	44 k
	ROV	1	34.48 k	3.45 k
	TBs	1	N/A	8.6 k

Table 23 presents the detailed costs and durations for different removal operations in Horns Rev I OWF. Similar to the previous case studies, 20% of weather delays are assumed in the time calculations. As can be seen from Table 23, the WT removal operations would take about 240 days, resulting in 3 days/turbine. The removal costs of WTs, foundations, OS, and MM are estimated to be about £44.2m, £63.3m, £3.8m, and £1m, respectively. The cost for cable removal operation is expected to be about £13m and the site clearance will cost around £9m. The total removal cost for this OWF is approximated at about £134m. It is worth mentioning that the fuel costs are also considered within the cost calculations of different removal operations in this case study.

Table 23. The costs and durations calculated for different removal operations in the Horn Rev I OWF

Activity	Total duration (days)	Weather delay (%)	Duration including weather delay (days)	Duration per unit (days/unit)	Removal cost (£)
WT removal	198.60	20%	238.30	2.98	44,177,677
Foundation removal	206.71	20%	248.05	3.10	63,317,435
OS removal	10.23	20%	12.27	12.27	3,761,559
MM removal	4.00	20%	4.81	4.81	998,566
Cable removal	64.65 (inter) 8.40 (export)	20%	77.60 (inter) 10.08 (export)	1.21 day/km (inter) 0.48 day/km (export)	13,076,840
Seabed clearance and restoration	65.43 (scour protection) 10.25 (rock dumping)	20%	74.91 (scour protection) 12.30 (rock dumping)	120 m^3/day (scour protection) 6.67 locations/day (rock dumping)	8,895,359 (scour protection) + 156,970 (rock dumping) = 9,052,329
Total costs:					134,384,407

Table 24 presents the emissions resulting from different pollutants for the Horns Rev I OWF. The table shows that the removal operations will generate about 722 tons, 109 tons, 20 tons, and 38,000 tons of NOx, SOx, PM, and CO2 emissions, respectively. From Table 24, it can also be concluded that the transportation of dismantled assets to the shore will result in about 21,423 tons of CO2 emissions which accounts for more than 50% of the total CO2 emissions of the project. This shows the necessity of developing new innovative transportation strategies for OWF decommissioning projects. Fig. 16 presents the percentage breakdown distribution of CO2 emission for each removal operation in Horns Rev I OWF. As it can be seen from this figure, the foundation removal operation is the major contributor to the CO2 emissions, accounting for more than 50% of overall CO2 emissions. Table 25 summarises the social costs resulting from the emissions, which shows about £6m of additional cost to the project. As shown in Fig. 17, more than 50% of social costs are related to the foundation removal operation. The comparison between the social costs of different removal operations is also illustrated in Fig. 18. Finally, the overall removal cost percentage break-down distribution for each removal operation is illustrated in Fig. 19. From Fig. 19, it can be seen that about 4.1% of the total cost is related to the social costs of emissions in the project.

Table 24. The emissions of different removal operations for Horns Rev I OWF (ton)

Activity	Emissions	NOx	SO_X	PM	CO_2
WT removal	$E_{\mathrm{tr}}^{\mathrm{WT}}$	32.59	4.92	0.91	1,704.50
	E_{o}^{WT}	110.44	16.66	3.08	5,775.69
	E_{WT}	143.04	21.57	3.99	7,480.19
Foundation removal	$E_{\mathrm{tr}}^{\mathrm{F}}$	232.42	35.05	6.48	12,154.18
	$E_{\mathrm{o}}^{\mathrm{F}}$	148.89	22.46	4.15	7,786.27
	E_{F}	381.31	57.51	10.63	19,940.45
OS removal	$E_{\mathrm{tr}}^{\mathrm{OS}}$	12.21	1.84	0.34	638.61
	$E_{\mathrm{o}}^{\mathrm{OS}}$	7.37	1.11	0.21	385.33
	E_{OS}	19.58	2.95	0.55	1,023.93
MM removal	$E_{\mathrm{tr}}^{\mathrm{MM}}$	4.51	0.68	0.13	235.57
	$E_{\mathrm{o}}^{\mathrm{MM}}$	2.43	0.37	0.07	127.13
	E_{MM}	6.94	1.05	0.19	362.70
Cable removal	E_{C}	57.75	8.71	1.61	3,019.92
Seabed clearance and restoration	$E_{\mathrm{tr}}^{\mathrm{SP}}$	70.19	10.59	1.96	3,670.49
	$E_{\mathrm{o}}^{\mathrm{SP}}$	39.48	5.96	1.10	2,064.65
	E_{SP}	109.67	16.54	3.06	5,735.1
	E_{RD}	3.78	0.57	0.10	197.8
	E_{SC}	113.45	17.11	3.16	5,932.9
Total:		722.06	108.90	20.12	37,760

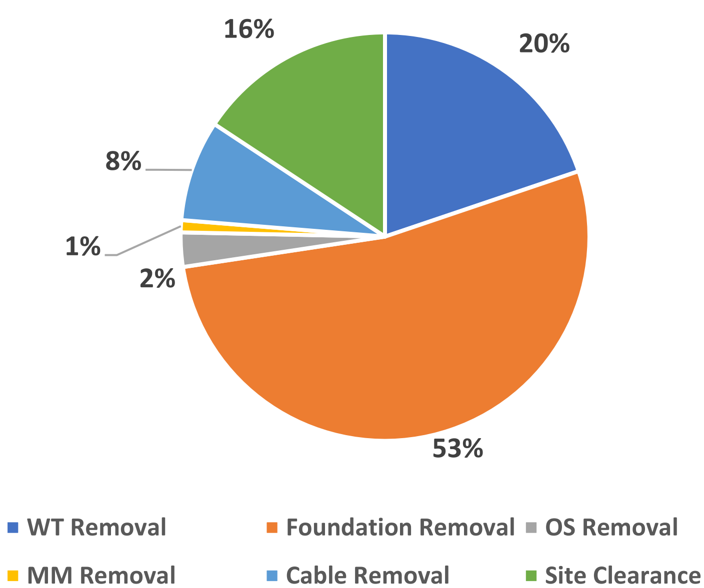


Fig. 16. The CO_2 emission percentage break-down distribution for each removal operation in Horns Rev I OWF

Table 25. The social costs related to the different pollutants in the Horns Rev I OWF

Activity	Social costs (£)				Total (£)
	NOx	SO_X	PM	CO_2	
WT removal	668,417	220,066	39,600	212,437	1,140,520
Foundation removal	1,781,845	586,644	105,564	566,309	3,040,362
OS removal	91,497	30,124	5,421	29,080	156,121
MM removal	32,411	10,671	1,920	10,301	55,302
Cable removal	269,855	88,845	15,987	85,766	460,453
Seabed clearance and restoration	530,154	174,545	31,409	168,494	904,601
Total	3,374,177	1,110,894	199,901	1,072,386	5,757,359

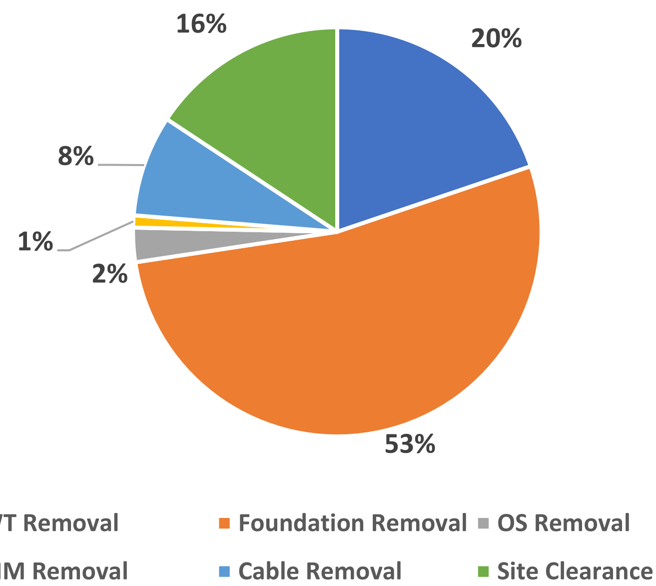


Fig. 17. The total social cost break-down distribution for each removal operation in Horns Rev I OWF

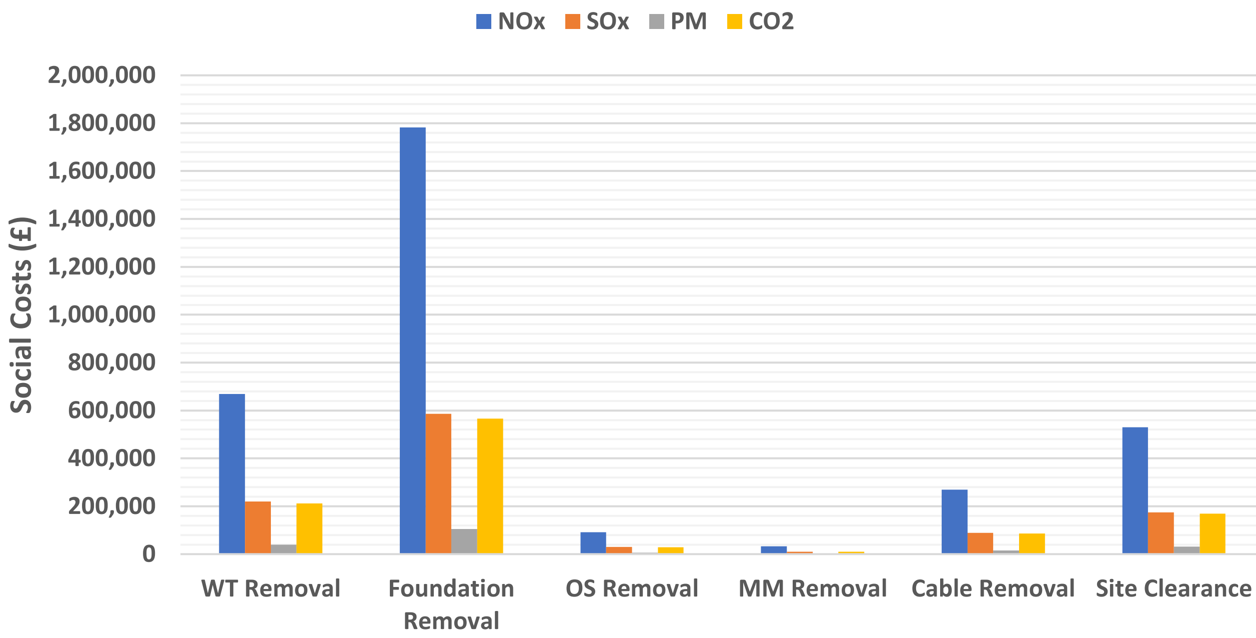


Fig. 18. The social costs of different pollutants resulted from different activities in Horns Rev I OWF

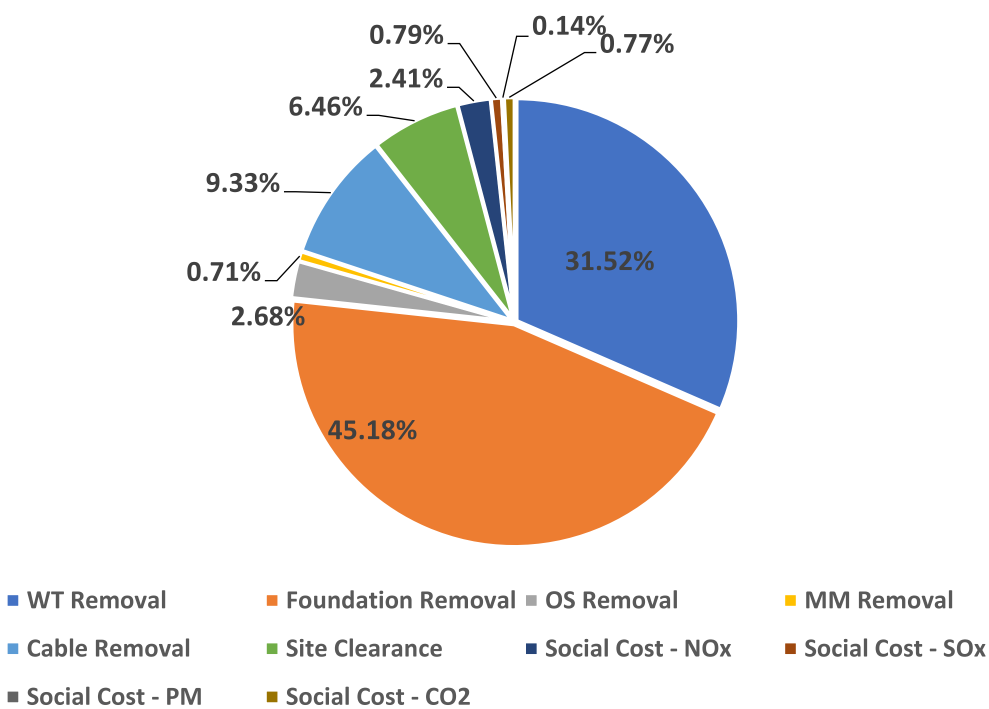


Fig. 19. The total cost percentage break-down distribution for each removal operation and pollutant in Horns Rev I OWF

5 Summary and Conclusions

This report investigated the cost and emission analyses of OWF decommissioning projects in the North Sea region. The main approach was to use the bottom-up formulations to model the cost and emissions of different removal operations. One of the main challenges in the cost and emission assessments of OWF decommissioning projects is the absence of reliable data due to the limited experience in the field. The cost and operational time parameters are significantly sensitive to a range of uncertain parameters, such as the project strategies, market situation, and site-specific conditions. The report assessed the decommissioning costs and emissions of three different OWF case studies in the North Sea region, including Lincs Limited, Gunfleet Sands, and Horns Rev I OWFs. In the investigated case studies, the costs of different removal operations, such as WT, foundation, OS, MM, and cable removal operations, were calculated based on the available data and experience as well as the best possible estimations. The costs of site clearance and restoration were also estimated in the Gunfleet Sands and Horns Rev I OWF case studies.

In the Lincs Limited case study, the obtained cost items were compared to the source results provided by the DP [14] of this OWF. The estimated costs suggested 14% and 31% errors for the WT and foundation removal operations. The differences in cost values may arise from different assumptions, such as the adopted removal and transportation strategies as well as vessel rates. In the Gunfleet Sands case study, the lower-bound and upper-bound cost estimations were calculated based on the available data from the previous projects. The results suggested how the available data and assumptions can result in remarkable changes in the overall decommissioning cost values. The minimum and maximum cost values for this case study highlighted the fact that there are significant uncertainties in the values of different cost and emission parameters which can dramatically affect the accuracy of the estimations.

The emission formulations presented in this report take into account the emissions resulting from both removals and transport operations. In the Horns Rev I case studies, in which all removal operations were considered, the results showed that the decommissioning activities will produce about 40,000 tonnes of CO_2 emissions. The result obtained for the Horns Rev I OWF also revealed that the transportation of dismantled assets to the shore will result in about 21,423 tonnes of CO_2 emissions which accounts for more than 50% of the total CO_2 emissions of the project. This highlights the necessity of the development of new innovative and sustainable transportation strategies for OWF decommissioning projects to reduce the overall emissions. The total social cost incurred by the emissions was also around £6 m for this OWF, which would also be avoidable through the sustainable removal approaches. Moreover, the costs and emissions of the site clearance and restoration as well as cable removal operations obtained for different case studies suggest that the leaving of cables and scour protections in situ is an attractive option from the economic and environmental viewpoints.

Appendix A. Cost Calculations

A.1. WTs Removal Cost

The total removal cost of the WTs can be mathematically written as:

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

where, $Cost_{\mathrm{WT}}$ represents the removal cost of the WTs (pounds), $C_{\mathrm{mob}}^{\mathrm{JUV}}$ is the mobilisation/demobilisation cost of the JUV (pounds), $C_{\mathrm{mob}}^{\mathrm{BV}}$ indicates the mobilisation/demobilisation cost of the BV (pounds), α is the number of employed BVs for the transportation, $C_{\mathrm{D}}^{\mathrm{JUV}}$ is the day rate of the JUV (pounds/day), $C_{\mathrm{D}}^{\mathrm{BV}}$ indicates the day rate of the BV (pounds/day), $C_{\mathrm{D}}^{\mathrm{TB}}$ is the daily rate for the TB (pounds/day), β is a constant parameter to consider the required number of TBs, and t_{WT} represents the total duration for the removal of each WT (hr). The value of β is equal to the number of BVs (i.e., $\beta = \alpha$) if a self-propelled JUV is used for the lifting process. Otherwise, another TB should also be considered for the JUV, i.e., $\beta = \alpha + 1$.

The removal duration of WTs t_{WT}, depends on the removal method. In the investigated case studies in this report, two different WT installation methods are considered, including Method I and Method IV which are fully explained in Ref. [27]. Fig. A.1.1 shows the different stages of WT removal operations for these two methods. In Method I, the WT blades are lifted in three separate lifts. In Method IV, the nacelle and two blades are dismantled in a single lift, which is usually referred to as the "bunny ear" configuration in literature.

The removal duration of WTs t_{WT} for each method can be expressed as follows [27]:

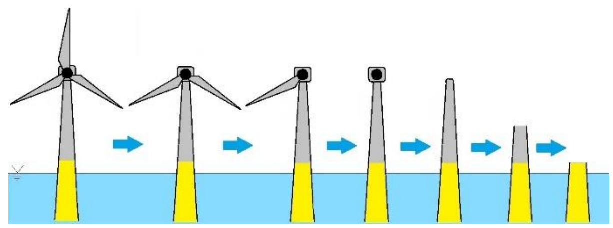
- Method I:

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

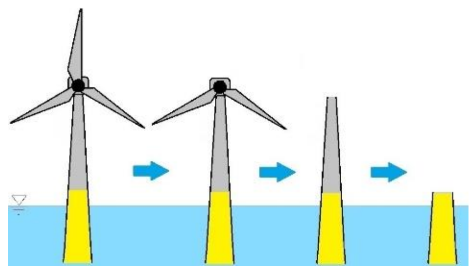
- Method V:

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

where, n_{t} is the number of WTs in the OWF, $t_{\mathrm{pos}}^{\mathrm{JUV}}$ represents the required time for the positioning of the JUV to start the removal operation (hr), $t_{\mathrm{up}}^{\mathrm{JUV}}$ is the jacking-up duration of the JUV (hr), t_{B} is the removal duration of an individual blade of WT (hr), t_{N} represents the dismantling duration of the nacelle (hr), t_{T} indicates the removal duration of the whole tower of the WT in a single lift operation (hr), $t_{N,R,2B}$ represents the removal duration for the nacelle with attached rotor and two blades (i.e., bunny ear configuration) in a single lift (hours), and $t_{\mathrm{down}}^{\mathrm{JUV}}$ is the jacking down duration of the JUV (hr).



a



b

Fig. A.1.1. Different WT removal methods: a) Method I and b) Method IV

A.2. Foundation Removal Cost

In Ref. [27], four different methods were discussed for foundation removal operations. In this report, different foundation removal strategies were implemented in different case studies. In the Lincs Limited and Gunfleet Sands OWF case studies, it is assumed that the OSV and JUV are jointly employed to perform the foundation removal operation. This scenario provides cheaper removal costs, as the day rate of the OSV is much cheaper than the JUV. However, a different removal strategy is considered for the Horns Rev I OWF due to the available information for this case study. In the Horns Rev I OWF, it is assumed that the foundation cutting and lifting process will be performed by JUV. According to Ref. [27], the foundation removal strategies in the mentioned case studies in this report can be described by two different methods explained below.

A.2.1. Method I

In the first method, it is assumed that both foundation cutting and lifting processes are performed by a JUV. BV(s) will be required to transport the dismantled components to the shore. The removal cost for this method can be formulated as follows:

$$Cost_{\mathrm{F}} = C_{\mathrm{mob}}^{\mathrm{JUV}} + \alpha C_{\mathrm{mob}}^{\mathrm{BV}} + C_{\mathrm{mob}}^{\mathrm{ROV}} + {}^{1}\!/_{24}\left(C_{\mathrm{D}}^{\mathrm{JUV}} + C_{\mathrm{D}}^{\mathrm{ROV}} + \alpha C_{\mathrm{D}}^{\mathrm{BV}} + \beta C_{\mathrm{D}}^{\mathrm{TB}}\right) \times t_{\mathrm{total}}^{\mathrm{JUV}} \qquad \text{(A.4)}$$

where, $Cost_{\mathrm{F}}$ represents the total foundation removal cost, $C_{\mathrm{mob}}^{\mathrm{JUV}}$ indicates the mobilisation/demobilisation cost of the JUV (pounds), α is the number of applied BVs for the transportation, $C_{\text{mob}}^{\text{BV}}$ indicates the mobilisation/demobilisation cost of the BV (pounds), $C_{\text{mob}}^{\text{ROV}}$ is the mobilisation cost of the ROV, $C_{\text{D}}^{\text{JUV}}$ is the day rate of the JUV (pounds/day), $C_{\text{D}}^{\text{ROV}}$ is the day rate of the ROV, C_{D}^{BV} indicates the day rate of the BV (pounds/day), C_{D}^{TB} is the day rate for the TB (pounds/day), $t_{\text{total}}^{\text{JUV}}$ is the total work duration of the JUV during the preparation, cutting, and lifting processes of the foundation (hr), and β is the number of TBs. The total foundation removal duration $t_{\text{total}}^{\text{JUV}}$ can be calculated by the following equation:

$$t_{\text{total}}^{\text{JUV}} = n_{\text{F}} \times \left(t_{\text{pos}}^{\text{JUV}} + t_{\text{up}}^{\text{JUV}} + t_{\text{P}} + t_{\text{C}} + t_{\text{L}}^{\text{JUV}} + t_{\text{down}}^{\text{JUV}}\right) \tag{A.5}$$

where, n_{F} is the number of foundations, $t_{\text{pos}}^{\text{JUV}}$ represents the time required for positioning the JUV to start the foundation removal operation (hr), $t_{\text{up}}^{\text{JUV}}$ is the jacking-up duration of the JUV, t_{P} indicates the time required to pump the mud inside the foundation to provide the required space for the cutter to access the cutting line (hr), t_{C} is the cutting duration of the foundation (hr), $t_{\text{L}}^{\text{JUV}}$ is the time required for lifting the foundation and placing it on the BV (hr), and $t_{\text{down}}^{\text{JUV}}$is the jacking-down duration (hr).

The time required for pumping the mud inside the foundation t_{P} can be obtained as follows:

$$t_{\text{P}} = \frac{V_{\text{pump}}}{Q_{\text{pump}}} \tag{A.6}$$

where, Q_{pump} is the pumping rate $(\frac{m^3}{hr})$ and V_{pump} represents the volume of the mud that is required to be pumped and removed (m^3). The pumping volume V_{pump} can be calculated by the following equation:

$$V_{\text{pump}} = \frac{\pi}{4} D^2 (d_{\text{c}} + e) \tag{A.7}$$

in which D (m) is the foundation diameter, d_{c} (m) is cutting depth below the mud line, and e is the additional space provided for the access of the cutter to the cutting line. The cutting duration of the foundation is obtained by $t_{\text{C}} = \nu_{\text{cut}} D$, in which ν_{cut} (hour/m) is the cutting rate per the foundation diameter.

A.2.2. Method II

The second method assumes that an OSV will be used as the support vessel for the preparation and cutting process of the foundation. Thereafter, a JUV will be employed to lift the foundation and place it on BV. Depending on the type of the JUV, one or two TBs are required to pull the JUV and BV. The rental rate of the OSV is significantly cheaper than the JUV which can potentially lead to significant savings in the overall removal costs. The foundation removal cost for this method can be written s follows:

$$Cost_{\mathrm{F}} = C_{\mathrm{mob}}^{\mathrm{JUV}} + \alpha C_{\mathrm{mob}}^{\mathrm{BV}} + C_{\mathrm{mob}}^{\mathrm{ROV}} + C_{\mathrm{D}}^{\mathrm{OSV}} \times t_{\mathrm{total}}^{\mathrm{OSV}} + {}^{1}\!/_{24}\left(C_{\mathrm{D}}^{\mathrm{JUV}} + \alpha C_{\mathrm{D}}^{\mathrm{BV}} + \beta C_{\mathrm{D}}^{\mathrm{TB}}\right) \times t_{\mathrm{total}}^{\mathrm{JUV}} + C_{\mathrm{D}}^{\mathrm{ROV}}\left(t_{\mathrm{total}}^{\mathrm{OSV}} + t_{\mathrm{total}}^{\mathrm{JUV}}\right) \tag{A.8}$$

where, $C_{\mathrm{D}}^{\mathrm{OSV}}$ indicates the day rate of the OSV (pounds), $t_{\mathrm{total}}^{\mathrm{OSV}}$ is the total working duration of the OSV for the foundation preparation (hr), $t_{\mathrm{total}}^{\mathrm{JUV}}$ is the total working duration of the JUV for lifting the foundation and placing it on the BV's deck (hr), and the definitions for the rest of the parameters are similar to those explained in the previous method.

The working duration of the OSV $t_{\mathrm{total}}^{\mathrm{OSV}}$ can be calculated as follows:

$$t_{\mathrm{total}}^{\mathrm{OSV}} = n_{\mathrm{F}} \times \left(t_{\mathrm{pos}}^{\mathrm{OSV}} + t_{\mathrm{P}} + t_{\mathrm{C}} + t_{\mathrm{move}}^{\mathrm{OSV}}\right) \tag{A.9}$$

where, n_{F} represents the number of foundations, $t_{\mathrm{pos}}^{\mathrm{OSV}}$ (hr) is the positioning time of the OSV, t_{P} (hr) and t_{C} (hr) are the pumping and cutting durations of the foundation, respectively, and $t_{\mathrm{move}}^{\mathrm{OSV}}$(hr) denotes the moving time of the OSV. The time required for pumping the mud inside the foundation t_{P} can be obtained as follows:

$$t_{\mathrm{P}} = \frac{V_{\mathrm{pump}}}{Q_{\mathrm{pump}}} \tag{A.10}$$

where, Q_{pump} ($\frac{m^3}{hr}$) is the pumping rate and V_{pump} (m^3) is the pumping volume. The pumping volume V_{pump} can be calculated as follows:

$$V_{\mathrm{pump}} = \frac{\pi}{4} D^2 (d_{\mathrm{c}} + e) \tag{A.11}$$

in which D (m) is the foundation diameter, d_{c} (m) is cutting depth below the mud line, and e is the additional space provided for the ease of access to the cutting line.

The cutting duration of the foundation is obtained by $t_{\mathrm{C}} = \nu_{\mathrm{cut}} D$, in which ν_{cut} (hour/m) is the cutting rate per the foundation diameter.

The total working duration of the JUV for lifting the foundation and placing it on the BV's deck $t_{\mathrm{total}}^{\mathrm{JUV}}$ can be obtained as follows:

$$t_{\mathrm{total}}^{\mathrm{JUV}} = n_{\mathrm{F}} \times \left(t_{\mathrm{pos}}^{\mathrm{JUV}} + t_{\mathrm{up}}^{\mathrm{JUV}} + t_{\mathrm{L}}^{\mathrm{JUV}} + t_{\mathrm{down}}^{\mathrm{JUV}}\right) \tag{A.12}$$

where, $t_{\mathrm{pos}}^{\mathrm{JUV}}$ is the required time for positioning the JUV for foundation removal (hr), $t_{\mathrm{up}}^{\mathrm{JUV}}$ is the time required for jacking up, $t_{\mathrm{L}}^{\mathrm{JUV}}$ is the time required for lifting the foundation and placing it on the BV (hr), and $t_{\mathrm{down}}^{\mathrm{JUV}}$is the jacking-down duration (hr).

A.3. OS and MM Removal Costs

The removal cost of the OS can be expressed as follows:

$$Cost_{\mathrm{OS}} = C_{\mathrm{mob}}^{\mathrm{JUV}} + C_{\mathrm{mob}}^{\mathrm{ROV}} + C_{\mathrm{mob}}^{\mathrm{BV}} + {}^{1}\!/_{24} \left(C_{\mathrm{D}}^{\mathrm{JUV}} + C_{\mathrm{D}}^{\mathrm{OSV}} + C_{\mathrm{D}}^{\mathrm{ROV}} + \alpha C_{\mathrm{D}}^{\mathrm{BV}} + \beta C_{\mathrm{D}}^{\mathrm{TB}}\right) \times t_{\mathrm{total}}^{\mathrm{OS}} \tag{A.13}$$

where, $Cost_{\mathrm{OS}}$ denotes the removal cost of the OS, $t_{\mathrm{total}}^{\mathrm{OS}}$ (hr) represents the total removal duration of the OS, including the topside and foundation, and the definitions for the rest of the parameters are similar to those explained for other removal operations. The total removal duration of the OS $t_{\mathrm{total}}^{\mathrm{OS}}$ can be calculated as follows:

- *If the foundation is a jacket structure*

$$t_{\mathrm{total}}^{\mathrm{OS}} = n_{\mathrm{OS}} \times \left(t_{\mathrm{pos}}^{\mathrm{JUV}} + t_{\mathrm{up}}^{\mathrm{JUV}} + t_{\mathrm{c,top}} + t_{\mathrm{L,top}} + t_{\mathrm{c,p}} + t_{\mathrm{L,j}} + t_{\mathrm{down}}^{\mathrm{JUV}}\right) \tag{A.14}$$

where, n_{OS} is the number of OSs in the wind farm, $t_{\mathrm{pos}}^{\mathrm{JUV}}$ is the required time for positioning the JUV for OS removal (hr), $t_{\mathrm{c,top}}$ indicates the cutting and disconnecting duration required for the topside removal (hr), $t_{\mathrm{L,top}}$ represents the lifting duration of the topside by the JUV (hr), $t_{\mathrm{c,p}}$ is the cutting duration of the piles under the seabed (hr), $t_{\mathrm{L,j}}$ is the time required by the JUV to lift the jacket structure (hr), and $t_{\mathrm{down}}^{\mathrm{JUV}}$is the jacking-down duration (hr).

- *If the foundation is a monopile structure*

$$t_{\mathrm{total}}^{\mathrm{OS}} = n_{\mathrm{OS}} \times \left(t_{\mathrm{pos}}^{\mathrm{JUV}} + t_{\mathrm{up}}^{\mathrm{JUV}} + t_{\mathrm{c,top}} + t_{\mathrm{L,top}} + t_{\mathrm{P}} + t_{\mathrm{C}} + t_{\mathrm{L}}^{\mathrm{JUV}} + t_{\mathrm{down}}^{\mathrm{JUV}}\right) \tag{A.15}$$

where, t_{P} (hr) and t_{C} (hr) are the pumping and cutting durations of the foundation, respectively, t_{C} represents the cutting duration (hr), and $t_{\mathrm{L}}^{\mathrm{JUV}}$ is the lifting duration of the monopile. The definitions for the rest of the parameters are similar to those explained in the previous section.

Since the removal of the topside of the MM includes a significantly lighter lifting operation, the lifting time for the top side of the MM is shorter than the lifting duration for the topside of the OS. In this case, the removal cost of the MM can be expressed as similar to Equations (A.13), (A.14), and (A.15). The differences are the durations for the $t_{\mathrm{c,top}}$, $t_{\mathrm{L,top}}$, t_{P} and t_{C}, which are assumed to be shorter for the MM than those for the OS.

A.4. Cable Removal Costs

The cable removal cost can be mathematically expressed as follows:

$$C_{\mathrm{C}} = C_{\mathrm{mob}}^{\mathrm{CLV}} + C_{\mathrm{mob}}^{\mathrm{ROV}} + \left(C_{\mathrm{D}}^{\mathrm{CLV}} + C_{\mathrm{D}}^{\mathrm{ROV}}\right)(t_{\mathrm{I}} + t_{\mathrm{E}}) \tag{A.16}$$

where, C_{C} represents the cable removal cost (pounds), $C_{\mathrm{mob}}^{\mathrm{CLV}}$ denotes the mobilisation cost of the CLV (pounds), and $C_{\mathrm{D}}^{\mathrm{CLV}}$ is the day rate of the CLV (pounds/day), $C_{\mathrm{D}}^{\mathrm{ROV}}$ is the day rate of the ROV, t_{I} and t_{E} are the cable removal duration (days) for the inner-array and export cables in a given wind farm, respectively. The cable removal durations are calculated as follows:

$$t_{\mathrm{I}} = \frac{L_{\mathrm{I}}}{r_{\mathrm{I}} \times IF_{\mathrm{I}}} \tag{A.17}$$

$$t_{\mathrm{E}} = \frac{L_{\mathrm{E}}}{r_{\mathrm{E}} \times IF_{\mathrm{E}}} \tag{A.18}$$

where, L_{I} indicates the length of the inter-array cables (km), L_{E} represents the length of the export cables (km), r_{I} is the cable installation rate for the inter-array cables (km/day), r_{E} is the cable installation rate for the export cables (km/day), IF_{I} is the IF for the inter-array cables, IF_{E} is the IF for the export cables.

A.5. Seabed Clearance and Restoration Costs

After the removal operations, some activities should be performed to return the seabed to its original state as much as possible. These activities include filling the holes on the seabed resulting from the removal operations and the removal of scour protections. The total cost related to the seabed clearance and restoration activities can be expressed as follows:

$$Cost_{\mathrm{SC}} = Cost_{\mathrm{SP}} + Cost_{\mathrm{RD}} \tag{A.19}$$

where, $Cost_{\mathrm{SC}}$ represents the total cost of the seabed clearance and restoration activities, $Cost_{\mathrm{SP}}$ is the cost of the scour protection removal operation, and $Cost_{\mathrm{RD}}$ denotes the cost related to the rock dumping operation.

The removal cost of the scour protection $Cost_{\mathrm{SP}}$ can be formulated as follows:

$$Cost_{\mathrm{SP}} = C_{\mathrm{mob}}^{\mathrm{DCBV}} + C_{\mathrm{mob}}^{\mathrm{BV}} + \alpha C_{\mathrm{mob}}^{\mathrm{ROV}} + {}^{1}/_{24} \left(C_{\mathrm{D}}^{\mathrm{DCBV}} + \alpha C_{\mathrm{D}}^{\mathrm{BV}} + \beta C_{\mathrm{D}}^{\mathrm{TB}} + C_{\mathrm{D}}^{\mathrm{ROV}} \right) \times t_{\mathrm{total}} \quad \text{(A.20)}$$

$$t_{\mathrm{total}} = (n_{\mathrm{t}} + n_{\mathrm{OS}} + 1) \times \left(t_{\mathrm{pos}}^{\mathrm{DCBV}} + t_{\mathrm{a}}^{\mathrm{DCBV}} \right) + \left(\sum_{i=1}^{n_{\mathrm{t}}} \frac{V_i^{\mathrm{WT}}}{r_{\mathrm{ret}}} + \sum_{i=1}^{n_{\mathrm{OS}}} \frac{V_i^{\mathrm{OS}}}{r_{\mathrm{ret}}} + \frac{V^{\mathrm{MM}}}{r_{\mathrm{ret}}} \right) \quad \text{(A.21)}$$

where, $Cost_{\mathrm{SP}}$ indicates the total removal cost of the scour protections in the wind farm, $C_{\mathrm{mob}}^{\mathrm{DBV}}$ is the mobilisation cost for the DCBV (pounds), $C_{\mathrm{mob}}^{\mathrm{BV}}$ is the mobilisation cost for the BV (pounds), $C_{\mathrm{D}}^{\mathrm{DCBV}}$ (pounds) represents the daily rate of the DCBV, $C_{\mathrm{D}}^{\mathrm{BV}}$ (pounds) is the daily rate of the BV, $C_{\mathrm{D}}^{\mathrm{TB}}$ (pounds) is the daily rate of the TBs, t_{total} indicates the total removal duration of the scour protections in the wind farm (hr), $t_{\mathrm{pos}}^{\mathrm{DCBV}}$ (hr) is the positioning duration of the DCBV to start the removal operation, V_i^{WT} (m^3) represents the scour protection material volume around the ith WT in the wind farm, r_{ret} (m^3/hour) is the removal rate of scour protection materials, n_{t} is the number of WTs in the wind farm, n_{OS} is the number of OSs in the wind farm, V_i^{OS} (m^3) represents the scour protection material volume around the ith OS in the wind farm, V^{MM} (m^3) indicates the scour protection material volume around the MM, $t_{\mathrm{a}}^{\mathrm{DCBV}}$ (hr) represents the time required by the DCBV to retrieve its anchors.

The rock dumping cost can be calculated as follows:

$$Cost_{\mathrm{RD}} = C_{\mathrm{mob}}^{\mathrm{RDV}} + C_{\mathrm{mob}}^{\mathrm{ROV}} + \left(C_{\mathrm{D}}^{\mathrm{RDV}} + C_{\mathrm{D}}^{\mathrm{ROV}} \right) \times t_{\mathrm{total}} \quad \text{(A.22)}$$

$$t_{\mathrm{total}} = \frac{(n_{\mathrm{t}} + n_{\mathrm{OS}} + 1)}{r_{\mathrm{rd}}} \quad \text{(A.23)}$$

where, $Cost_{\mathrm{RD}}$ (pounds) represents the cost of the rock dumping, $C_{\mathrm{mob}}^{\mathrm{RDV}}$ (pounds) is the mobilisation cost of the RDV, $C_{\mathrm{D}}^{\mathrm{RDV}}$ (pounds) indicates the day rate of the RDV, t_{total} (days) is the total rock dumping operation, and r_{rd} is the rock dumping rate (locations/day).

Appendix B. Emission Calculations

For each removal operation in an OWF decommissioning project, the overall emissions can be decomposed into two parts, including the emissions resulting from the crane operations and the emissions related to the transportation of dismantled parts to the shore. The emission amounts are directly related to the fuel consumption and emission rates of the employed vessels/equipment. The total emissions E_{total} resulted from the OWF decommissioning can be expressed as follows:

$$E_{\mathrm{total}} = E_{\mathrm{WT}} + E_{\mathrm{F}} + E_{\mathrm{OS}} + E_{\mathrm{MM}} + E_{\mathrm{C}} + E_{\mathrm{SC}} \tag{B.1}$$

where, E_{WT}, E_{F}, E_{OS}, E_{MM}, E_{C}, and E_{SC} represent the emissions resulting from the WT removal, foundation removal, OS removal, MM removal, cable removal, and seabed clearance operations, respectively. In the following subsections, the emissions related to each activity will be discussed in detail.

B.1. WT Removal Emissions

The emissions resulted from the WT removal operations E_{WT} can be written as:

$$E_{\mathrm{WT}} = E_{\mathrm{o}}^{\mathrm{WT}} + E_{\mathrm{tr}}^{\mathrm{WT}} \tag{B.2}$$

where, $E_{\mathrm{o}}^{\mathrm{WT}}$ represents the emissions resulting from the crane operations and repositioning of the vessels in WT removal operation and $E_{\mathrm{tr}}^{\mathrm{WT}}$ indicates the emissions resulted from the transportation of dismantled WT components to the shore. As the JUVs, BVs, and TBs are usually employed for WT removal operations, their fuel consumptions and emission rates need to be considered in the emission calculations.

The emissions resulted from the crane operations and the repositioning of the vessels $E_{\mathrm{o}}^{\mathrm{WT}}$ (tons) can be expressed as follows:

$$E_{\mathrm{o}}^{\mathrm{WT}} = 0.001 e_{\mathrm{r}} f_{\mathrm{JUV}} t_{\mathrm{WT}} \tag{B.3}$$

where, t_{WT} (hr) represents the total removal duration of WTs obtained from Equations (A.2) or (A.3), e_{r} (kg/metric ton) is the emission factor defined for a specific pollutant, and f_{JUV} (ton/hour) is the fuel consumption of JUV (ton/hour).

The emissions resulted from the transportation of dismantled components to the shore $E_{\mathrm{tr}}^{\mathrm{WT}}$ depend on the project strategy and can be calculated by the following equations:

- If BVs are used for transportation:

$$E_{\mathrm{tr}}^{\mathrm{WT}} = 0.001\, \beta e_{\mathrm{r}} f_{\mathrm{TB}} (2t_{\mathrm{tr}}^{\mathrm{WT}} + t_{\mathrm{WT}}) \tag{B.4}$$

- If JUVs are used for transportation:

$$E_{\mathrm{tr}}^{\mathrm{WT}} = 0.001\, e_{\mathrm{r}} f_{\mathrm{JUV}} (2t_{\mathrm{tr}}^{\mathrm{WT}}) \tag{B.5}$$

where, e_{r} (kg/metric ton) is the emission factor, f_{TB} (ton/hour) is the fuel consumption of TB, t_{WT} (hr) represents the total removal duration of WTs obtained from Equations (A.2) or (A.3), and $t_{\mathrm{tr}}^{\mathrm{WT}}$ (hr) indicates the transportation duration which can be calculated for different cases as below:

- If BVs are used for transportation:

$$t_{\mathrm{tr}}^{\mathrm{WT}} = fix\left(\frac{n_{\mathrm{t}}}{n_{\mathrm{CWT}}}\right) \times \left(\frac{d_{\mathrm{port}}}{1.852 \times \upsilon_{\mathrm{TB}}} + t_{\mathrm{ol}} + t_{\mathrm{s}}\right) \tag{B.6}$$

- If JUVs are used for transportation:

$$t_{\mathrm{tr}}^{\mathrm{WT}} = \mathrm{fix}\left(\frac{n_{\mathrm{t}}}{n_{\mathrm{CWT}}}\right) \times \left(\frac{d_{\mathrm{port}}}{1.852 \times \upsilon_{\mathrm{JUV}}} + t_{\mathrm{ol}}\right) \tag{B.7}$$

where $\mathrm{fix}(.)$ is a function that rounds up the input number, n_{t} is the number of WTs, n_{CWT} is the number of WT units transported in each cycle or trip, d_{port} (km) is the distance of the recycling port from the wind farm site, υ_{TB} (knots) indicates the towing speed of the BVs, υ_{JUV} (knots) is the transit speed of the JUV, t_{ol} is the total off-loading duration of each cycle at the port, and t_{s} is the service time of the BV. In this report, the off-loading duration is considered equal to 12 hours and the service duration for the BV is assumed as 1 day for the Lincs Limited and Gunfleet Sands OWFs. For the Horns Rev I case study, the service duration of BV was not considered in the calculations.

B.2. Foundation Removal Emissions

The emissions resulting from the foundation removal operation can be calculated by using the following equation:

$$E_{\mathrm{F}} = E_{\mathrm{o}}^{\mathrm{F}} + E_{\mathrm{tr}}^{\mathrm{F}} \tag{B.8}$$

where, $E_{\mathrm{o}}^{\mathrm{F}}$ denotes the emissions resulting from the crane operations and the repositioning of the vessels in foundation removal operations and $E_{\mathrm{tr}}^{\mathrm{F}}$ indicates the emissions resulted from the transportation of dismantled foundations to the shore.

The emissions resulted from the crane operations and the repositioning of the vessels in foundation removal $E_{\mathrm{o}}^{\mathrm{F}}$ depends on the removal approaches, which were explained earlier in Section A.2. In

Method I, the JUVs are used to support the cutting process and lifting of the foundation to a BV, while Method II uses a combination of OSV and JUV during the cutting and lifting processes. Therefore, the total emissions for the crane operations and the repositioning of the vessels $E_{\mathrm{o}}^{\mathrm{F}}$, can be expressed by the following equations for each approach:

- Method I:
  $$E_{\mathrm{o}}^{\mathrm{F}} = 0.001\, e_{\mathrm{r}}\, f_{\mathrm{JUV}}\, t_{\mathrm{total}}^{\mathrm{JUV}} \tag{B.9}$$
- Method II:
  $$E_{\mathrm{o}}^{\mathrm{F}} = e_{\mathrm{r}}\left(f_{\mathrm{OSV}} t_{\mathrm{total}}^{\mathrm{OSV}} + f_{\mathrm{JUV}} t_{\mathrm{total}}^{\mathrm{JUV}}\right) \tag{B.10}$$

where, f_{OSV} and f_{JUV} are the fuel consumptions of the OSV and JUV in ton/hour, respectively, $t_{\mathrm{total}}^{\mathrm{JUV}}$ (hr) is the work duration of the JUV in the foundation removal operation obtained from Equation (A.5), and $t_{\mathrm{total}}^{\mathrm{OSV}}$ (hr) represents the work duration of the OSV in foundation removal obtained from Equation (A.9).

The emissions resulting from the transportation of foundations can be written as:

$$E_{\mathrm{tr}}^{\mathrm{F}} = \beta e_{\mathrm{r}} f_{\mathrm{TB}}\left(2 t_{\mathrm{tr}}^{\mathrm{F}} + t_{\mathrm{total}}^{\mathrm{JUV}}\right) \tag{B.11}$$

where, $t_{\mathrm{total}}^{\mathrm{JUV}}$ (hr) represents the total working duration of the JUV in the removal of foundation yielded by Equation (A.5), $t_{\mathrm{tr}}^{\mathrm{F}}$(hr) is the transport duration of foundations to the port, and the definitions for the rest of the parameters are similar to those in Equations (B.9) or (B.10). The parameter $t_{\mathrm{tr}}^{\mathrm{F}}$ is obtained by considering the distance between the wind farm site and the port as follows:

$$t_{\mathrm{tr}}^{\mathrm{F}} = \mathrm{fix}\left(\frac{n_{\mathrm{F}}}{n_{\mathrm{CF}}}\right) \times \left(\frac{d_{\mathrm{port}}}{1.852 \times \upsilon_{\mathrm{TB}}} + t_{\mathrm{total}}^{\mathrm{JUV}}\right) \tag{B.12}$$

where $\mathrm{fix}(.)$ represents the fix function, n_{F} is the number of foundations, n_{CF} is the number of foundations being transported in each cycle or trip, d_{port} (km) is the distance of the recycling port from the wind farm site, and υ_{TB} (knots) indicates the towing speed of the TBs.

B.3. OS and MM Removal Emissions

As was discussed in Section A.3, the removal cost formulation for the OS and MM are similar. Hence, the emission formulations presented in this section are applicable for both of these units. The emissions for the OS removal operation E_{OS}, can be formulated as follows:

$$E_{\mathrm{OS}} = E_{\mathrm{o}}^{\mathrm{OS}} + E_{\mathrm{tr}}^{\mathrm{OS}} \tag{B.13}$$

where, $E_{\mathrm{o}}^{\mathrm{OS}}$ represents the emissions resulting from the vessels/equipment involved in the cutting and lifting processes of OS components and $E_{\mathrm{tr}}^{\mathrm{OS}}$ indicates the emissions yielded by the transport operation of dismantled parts of OS to the shore.

In the cost calculation for OS removal operation discussed in Section A.3, the emissions resulting from the OS cutting and lifting processes can be calculated by the following equation:

$$E_{\mathrm{o}}^{\mathrm{OS}} = e_{\mathrm{r}} f_{\mathrm{JUV}} t_{\mathrm{total}}^{\mathrm{OS}} \tag{B.14}$$

where, $t_{\mathrm{total}}^{\mathrm{OS}}$ (hr) is the total OS removal duration obtained from Equations (A.14) or (A.15).

The transport emissions can be calculated using the following formula:

$$E_{\mathrm{tr}}^{\mathrm{OS}} = \beta e_{\mathrm{r}} f_{\mathrm{TB}} \left(2 t_{\mathrm{tr}}^{\mathrm{OS}} + t_{\mathrm{total}}^{\mathrm{OS}}\right) \tag{B.15}$$

where, $t_{\mathrm{tr}}^{\mathrm{OS}}$ (hr) represents the transport duration for the OS removal and $t_{\mathrm{total}}^{\mathrm{OS}}$ (hr) indicates the total OS removal duration obtained from Equations (A.14) or (A.15). The transport duration of the OS removal operation $t_{\mathrm{tr}}^{\mathrm{OS}}$ is obtained by considering the distance and speed parameters as follows:

$$t_{\mathrm{tr}}^{\mathrm{OS}} = n_{\mathrm{OS}} \times \frac{d_{\mathrm{port}}}{1.852 \times \upsilon_{\mathrm{TB}}} \tag{B.16}$$

where, n_{OS} is the number of OSs in the wind farm, the υ_{TB} is towing speed, and d_{port} is the distance between the wind farm site and the port.

B.4. Cable Removal Emissions

As the cables are removed and transported by the CVL, the emissions resulting from the removal and transportation activities in the cable removal operation $E_{\mathrm{o}}^{\mathrm{C}}$, can be expressed by the following formula:

$$E_{\mathrm{O}}^{\mathrm{C}} = e_{\mathrm{r}} f_{\mathrm{CLV}} (t_{\mathrm{I}} + t_{\mathrm{E}}) \tag{B.17}$$

where, f_{CLV} represents the fuel consumption of the CLV in ton/hour, t_{I} (hr) is the inter-array cable removal duration obtained from Equation (A.17), and t_{E} (hr) indicates the removal duration of the export cables calculated from Equation (A.18).

B.5. Emissions for the Seabed Clearance and Restoration

As was discussed in Section A.5, the seabed clearance and restoration operations include the scour protection removal and rock dumping activities. Therefore, the total emissions for the seabed clearance and restoration activities E_{SC}, is expressed by the following equation:

$$E_{\mathrm{SC}} = E_{\mathrm{SP}} + E_{\mathrm{RD}} \tag{B.18}$$

where, E_{SP} (ton) indicates the emissions resulted from the scour protection removal and E_{RD} represents the emissions related to the rock dumping activities.

The emissions generated by the scour protection removal E_{SP} can be split up into the operational and transport parts as follows:

$$E_{\mathrm{SP}} = E_{\mathrm{O}}^{\mathrm{SP}} + E_{\mathrm{tr}}^{\mathrm{SP}} \tag{B.19}$$

where $E_{\mathrm{O}}^{\mathrm{SP}}$ represents the emissions related to the scour protection removal operations and $E_{\mathrm{tr}}^{\mathrm{SP}}$ indicates the emissions generated by the transportation of removed scour protection materials to the shore.

The emissions resulted from the scour protection removal operations $E_{\mathrm{O}}^{\mathrm{SP}}$ can be written in the following form:

$$E_{\mathrm{O}}^{\mathrm{SP}} = e_{\mathrm{r}} f_{\mathrm{DCBV}} t_{\mathrm{total}} \tag{B.20}$$

where, f_{DCBV} is the fuel consumption of the DCBV in tons/hr and t_{total} (hr) is the total removal duration of the scour protections in the wind farm calculated from Equation (A.21).

The emissions related to the transportation activities of the scour protection materials to the shore $E_{\mathrm{tr}}^{\mathrm{SP}}$ is obtained by the following equation:

$$E_{\mathrm{tr}}^{\mathrm{SP}} = \beta e_{\mathrm{r}} f_{\mathrm{TB}} t_{\mathrm{total}} \tag{B.21}$$

where, t_{total} is the total scour protection removal duration obtained from Equation (A.21) and β is the number of TBs employed to tow the BVs.

The emissions generated by the rock dumping activity E_{RD} can be calculated as follows:

$$E_{\mathrm{RD}} = e_{\mathrm{r}} f_{\mathrm{RDV}} t_{\mathrm{total}} \tag{B.22}$$

where, f_{RDV} is the fuel consumption of the RDV in tons/hour and t_{total} (hr) is the total rock dumping duration obtained from Equation (A.23).

Appendix C. Emission Factors

As it can be seen from the formulations described in Appendix B, the emissions are calculated based on the emission factors and fuel consumption. Table B.1 lists the emissions factors for different pollutants. In addition, Table B.2 lists the fuel consumption of different vessels employed in OWF decommissioning operations.

Table C.1. Emission factors for different pollutants in kg/metric ton [29]

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

Table C.2. Fuel consumption parameters for different removal activities [30]

Fuel parameter	Fuel type	Fuel consumption (ton/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 tons/day

Appendix D. Social Costs

The social cost is an attempt to put a price on emissions. The social cost is used to help policymakers determine whether the costs and benefits of a proposed policy to curb climate change are justified. The social costs related to the emissions of various pollutants can be calculated by multiplying the emission values by the social cost factors as given in Table D.1 [31].

Table D.1. Social cost factors for each pollutant [31]

Pollutant	Social cost per metric ton
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£	

References

[1] UU.NN. Kyoto protocol to the united nations framework Kyoto protocol to the united nations framework Rev. Eur. Community Int. Environ. Law, 7 (1998), pp. 214-217

[2] UU.NN. Approval of the Paris agreement Conv. Framew. Clim. Change, 70371 (2015), pp. 1-40.

[3] 2030 Climate and Energy Framework. [online] Available at: <https://www.iea.org/policies/1494-2030-climate-and-energy-framework> [Accessed 16 March 2022]

[4] IEA. Global energy & CO2 status report 2019: Emissions. [online] Available at: <https://www.iea.org/reports/global-energyco2-status-report-2019> [Accessed 17 March 2022]

[5] Vieira M, Snyder B, Henriques E, Reis L. European offshore wind capital cost trends up to 2020. Energy Policy 2019;129:1364–71.

[6] Arapogianni, A., Genachte, A.B., Ochagavia, R.M., Vergara, J.P., Castell, D., Tsouroukdissian, A.R., et al. 2013, Deep water-the next step for offshore wind energy, European Wind Energy Association (EWEA), accessed 6 July 2021, <https://windeurope.org/about-wind/reports/deep-water/>.

[7] Wind Europe Business Intelligence, T Remy, and A Mbistrova. Offshore wind in europe - key trends and statistics 2018. Wind Europe: Brussels, Belgium, 2019.

[8] Weston D. Dong announces Vindeby decommissioning, Wind Power Monthly. accessed 6 July 2021, <https://www.windpowermonthly.com/article/1382887/dong-announces-vindeby-decommissioning>; 2016.

[9] DecomTools, Interreg VB North Sea Region Programme, accessed 6 July 2021, <https://northsearegion.eu/decomtools>.

[10] Wind O. Vattenfall wraps up first ever offshore wind farm decommissioning. accessed 6 July 2021, <https://www.offshorewind.biz/2016/01/25/vattenfall-wraps-up-first-ever-offshore-wind-farm-decommissioning/>; 2016.

[11] ZITON. ZITON completes decommissioning of Utgrunden Offshore Windfarm. accessed 6 July 2021, <https://ziton.eu/ziton-completes-decommisioning-of-utgrunden-offshore-windfarm>; 2018.

[12] Decommissioning of offshore renewable energy installations under the Energy Act 2004: Guidance notes for the industry. Department of Energy & Climate Change. UK Government. 2011. [online] Available at: <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/80786/orei_guide.pdf> [Accessed 18 Nov 2021]

[13] Offshore renewable energy: decommissioning guidance. [online] available at: <https://www.gov.scot/publications/decommissioning-offshore-renewable-energy-installations-scottish-waters-scottish-part-renewable-energy-zone-under-energy-act-2004-guidance-notes-industry-scotland/> [Accessed 10 Nov 2021]

[14] Lincs Offshore Wind Farm Decommissioning Plan. Lincs Wind farm Limited. [online] available at: < https://www.yumpu.com/en/document/view/34957343/lincs-offshore-wind-farm-decomissioning-plan-centrica> [Accessed 26 Nov 2021]

[15] Lincs offshore wind farm. Orsted. [online] Available at: <https://orstedcdn.azureedge.net/-/media/www/docs/corp/uk/updated-project-summaries-06-19/190423_ps_lincs-web_aw.ashx?la=en&rev=b2829a1618ec4ac582413dfc2a4e9a63&hash=9661609ae1e7677a7f1dd2d502f3dd6a> [Accessed 4 April 2022]

[16] Gunfleet Sands offshore wind farm. Ørsted. [online] Available at: <https://orstedcdn.azureedge.net/-/media/www/docs/corp/uk/updated-project-summaries-06-19/190514_gunfleet-sands-web_aw.ashx?la=en&rev=363dbb3179f340ff9bdb5b23a512d37a&hash=5f4c45df5f670cd7f041cfbe87543b50> [Accessed 8 April 2022]

[17] Preliminary Information Memorandum, Gunfleet Sands Offshore Transmission Assets. [online] Available at: <https://www.ofgem.gov.uk/ofgem-publications/50829/gunfleet-sands-project-specific-preliminary-information-memorandum-pim.pdf> [Accessed 8 March 2022]

[18] Gunfleet Sands 2 Offshore Wind Farm Environmental Statement. June 2007. [online] Available at: <https://tethys.pnnl.gov/sites/default/files/publications/GunfleetSands2-ES-2007.pdf> [Accessed 10 March 2022]

[19] Gunfleet Sands offshore construction. [online] Available at: <https://www.pmsc.org.uk/misc/offshore%20construction%20Aug%202008-lowres.pdf> [Accessed 15 March 2022]

[20] Jalili, S., Maheri, A., Ivanovic, A. Cost Modelling For Offshore Wind Farm Decommissioning. 2021, DecomTools. [online] Available at: <https://northsearegion.eu/decomtools/news/cost-modelling-for-offshore-wind-farm-decommissioning/> [Accessed 17 March 2022]

[21] Horns Rev Offshore Wind Farm. [online] Available at: <https://www.power-technology.com/projects/hornsreefwind/> [Accessed 27 March 2022]

[22] DONG Energy and Vattenfall. The Danish Offshore Wind Farm Demonstration Project: Horns Rev and Nysted Offshore Wind Farms. 2005. [online] Available at: <https://tethys.pnnl.gov/sites/default/files/publications/Horns-Rev-Nysted-2006.pdf> [Accessed 7 April 2022]

[23] Elsamprojekt A/S. Horns Rev Offshore Wind Farm Environmental Impact Assessment. 2000. [online] Available at: <https://tethys.pnnl.gov/sites/default/files/publications/HornsRevOffshoreWF.pdf> [Accessed 20 Jan 2022]

[24] Leonhard, S,B,, Pedersen, J. Hard Bottom Substrate Monitoring Horns Rev Offshore Wind Farm. Annual Status Report 2003. [online] Available at: <https://www.eib.org/attachments/pipeline/20070322_nts_en.pdf> [Accessed 20 Jan 2022]

[25] Installing subsea cables at Horns Rev, Europe's 1st commercial wind farm situated in the North Sea. Global Offshore. [online] Available at: < https://globaloffshore.co.uk/wp-content/uploads/2018/11/Horns-Rev-Case-Study-GO035-v1.pdf> [Accessed 26 Jan 2022]

[26] Ian Baring-Gould. Offshore Wind Plant Electrical Systems. BOEM Offshore Renewable Energy Workshop. 2014. [online] Available at: <https://www.boem.gov/sites/default/files/about-boem/BOEM-Regions/Pacific-Region/Renewable-Energy/6-Ian-Baring-Gould---BOEM-Offshore-Wind-Plant-Electrical-Systems-CA.pdf> [Accessed 26 Jan 2022]

[27] Leonhard, S.B., Stenberg, C., Støttrup, J. Effect of the Horns Rev 1 offshore wind farm on fish communities: follow-up seven years after construction. Danish Energy Authority. [online] Available at: <https://tethys.pnnl.gov/publications/effect-horns-rev-1-offshore-wind-farm-fish-communities-follow-seven-years-after-0> [Accessed 10 April 2022]

[28] Lacal-Aránteguia, R., Yustab, J.M., Domínguez-Navarrob, J. A. Offshore wind installation: Analysing the evidence behind improvements in installation time. Renewable and Sustainable Energy Reviews. 2018, 92: 133-145.

[29] International Maritime Organization (IMO), 2009. Second IMO GHG Study 2009.

[30] Arvesen, Anders and Birkeland, Christine and Hertwich, Edgar G. The Importance of Ships and Spare Parts in LCAs of Offshore Wind Power. Environmental science & technology 2013, 47(6): 2948-2956

[31] Samoteskul, K., Firestone, J., Corbett, J., Callahan, J. Changing vessel routes could significantly reduce the cost of future offshore wind projects. Journal of Environmental Management 2014,141:146-154.