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LCI METHODOLOGY AND DATABASES

# An economic assessment framework for decommissioning of offshore wind farms using a cost breakdown structure

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## Abstract

**Purpose** As wind power generation increases globally, there will be a substantial number of wind turbines that need to be decommissioned in the coming years. It is crucial for wind farm developers to design safe and cost-effective decommissioning plans and procedures for assets before they reach the end of their useful life. Adequate financial provisions for decommissioning operations are essential, not only for wind farm owners but also for national governments. Economic analysis approaches and cost estimation models therefore need to be accurate and computationally efficient. Thus, this paper aims to develop an economic assessment framework for decommissioning of offshore wind farms using a cost breakdown structure (CBS) approach.

**Methods** In the development of the models, all the cost elements and their key influencing factors are identified from literature and expert interviews. Similar activities within the decommissioning process are aggregated to form four cost groups including: planning and regulatory approval, execution, logistics and waste management, and post-decommissioning. Some mathematical models are proposed to estimate the costs associated with decommissioning activities as well as to identify the most critical cost drivers in each activity group. The proposed models incorporate all cost parameters involved in each decommissioning phase for more robust cost assessment.

**Results and discussion** A case study of a 500 MW baseline offshore wind farm is proposed to illustrate the models' applicability. The results show that the removal of wind turbines and foundation structures is the most costly and lengthy stage of the decommissioning process due to many requirements involved in carrying out the operations. Although inherent uncertainties are taken into account, cost estimates can be easily updated when new information becomes available. Additionally, further decommissioning cost elements can be captured allowing for sensitivity analysis to be easily performed.

**Conclusions** Using the CBS approach, cost drivers can be clearly identified, revealing critical areas that require attention for each unique offshore wind decommissioning project. The CBS approach promotes adequate management and optimisation of identified key cost drivers, which will enable all stakeholders involved in offshore wind farm decommissioning projects to achieve cost reduction and optimal schedule, especially for safety-critical tasks.

**Keywords** Wind energy · Decommissioning · Offshore wind farm · Life-cycle costing · Cost breakdown structure (CBS)

## Nomenclature

| | |
|---|---|
| $\alpha$ | Percentage of contingency provisions from total decommissioning cost |
| $\beta$ | Percentage of planning and project management cost from total decommissioning cost |
| $A_{WF}$ | Area of wind farm |
| $C_{\mathrm{accom}}$ | Cost of personnel accommodation |
| $C_{\mathrm{amend}}$ | Cost of amending decommissioning plan |
| $C_{\mathrm{audit}}$ | Audit cost |
| $C_{\mathrm{cable\ decom}}$ | Cost of cable decommissioning |
| $C_{\mathrm{Consult}}$ | Consulting cost |
| $C_{\mathrm{conting}}$ | Contingency cost |
| $C_{\mathrm{decom-total}}$ | Total cost of decommissioning |
| $C_{\mathrm{disc}}$ | Cost of disconnection from grid |

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| | |
|---|---|
| $C_{\mathrm{E-Plan}}$ | Cost of engineering planning |
| $C_{\mathrm{EIA-Survey}}$ | Cost of environmental impact assessment survey |
| $C_{\mathrm{eqt/day}}$ | Cost per day of the equipment required for removal activities |
| $C_{\mathrm{EX}}$ | Cost of offshore marine activity execution |
| $C_{\mathrm{fixt.\,/unit}}$ | Cost per unit of the fixture required for lifting wind turbine towers |
| $C_{\mathrm{insure}}$ | Insurance cost |
| $C_{\mathrm{i/day}}$ | Daily rental rate of each vessel |
| $C_{\mathrm{k/day}}$ | Crew labour cost per day |
| $C_{L\,\&\,R}$ | Cost of lifting and removal |
| $C_{\mathrm{landfill}}$ | Cost of landfill |
| $C_{Lo\,\&\,WM}$ | Cost of logistics and waste management |
| $C_{\mathrm{logistics}}$ | Cost of logistics |
| $C_{\mathrm{misc}}$ | Miscellaneous cost |
| $C_{\mathrm{Nav-mark}}$ | Cost of navigation markings |
| $C_{\mathrm{OSS-decom}}$ | Cost of offshore substation decommissioning |
| $C_{P\,\&\,RC}$ | Cost of planning and regulatory approval |
| $C_{P-\mathrm{Decomm}}$ | Cost of post-decommissioning |
| $C_{\mathrm{Permit}}$ | Cost of obtaining permits for decommissioning activities |
| $C_{PM}$ | Cost of project management |
| $C_{\mathrm{port/annum}}$ | Cost of port rental per annum |
| $C_{\mathrm{port}}$ | Cost of port rental, equipment and other services |
| $C_{\mathrm{prep}}$ | Cost of turbine preparation |
| $C_{RA}$ | Regulatory approval |
| $C_{\mathrm{rem}}$ | Cost of remediation |
| $C_{\mathrm{revision}}$ | Cost of revising the decommissioning plan |
| $C_{Sc}$ | Cost of site clearance |
| $C_{Sm}$ | Cost of site monitoring |
| $C_{\mathrm{surv}}$ | Cost of seabed surveys |
| $C_{\mathrm{truck/km}}$ | Cost per kilometre for a truck to transport materials to processing facilities |
| $C_{w-\mathrm{OTransp}}$ | Cost of waste transportation |
| $C_{w-\mathrm{proc}}$ | Cost of waste processing |
| $C_{WM}$ | Cost of waste management |
| $K$ | Constant |
| $N_{\mathrm{fixt}}$ | Number of fixtures required for lifting wind turbine towers. |
| $N_i$ | Number of vessels required |
| $N_k$ | Number of personnel |
| $N_{WT}$ | Number of wind turbines |
| $N_\gamma$ | Number of trips required to shore |
| $r$ | Discount rate |
| $R(t)$ | Net cash flow |
| $t_{\mathrm{cable-decom}}$ | Time for decommissioning of inter-array and export cables |
| $t_j$ | Time needed to complete all offshore marine activities/tasks |
| $t_{L\,\&\,R-B\,\&\,N}$ | Time for lifting and removal of blade and nacelle |
| $t_{L\,\&\,R-\mathrm{found}}$ | Time for lifting and removal of foundation structures |
| $t_{L\,\&\,R-\mathrm{misc}}$ | Time for lifting and removal of miscellaneous components |
| $t_{L\,\&\,R-T\,\&\,TP}$ | Time for lifting and removal of tower and transition piece |
| $t_{L\,\&\,R-WTG}$ | Time for lifting and removal of wind turbines |
| $t_{MG-\mathrm{remov}}$ | Time for removal of marine growth |
| $t_{OSS-\mathrm{drain}}$ | Time for offshore substation draining |
| $t_{OSS-\mathrm{decom}}$ | Time for offshore substation decommissioning |
| $t_{\mathrm{pre-survey}}$ | Time for pre-decommissioning survey |
| $t_{\mathrm{prep}}$ | Time for preparation of wind turbines for removal |
| $t_{WT-\mathrm{drain}}$ | Time to drain lubricating fluids |
| $t_\gamma$ | Distance to and from shore |
| $W_j^R$ | Weight of recyclable materials |
| $W_{\mathrm{truck}}$ | Capacity of truck |
| $Wt_j$ | Weight of materials |

## 1 Introduction

Offshore wind energy has been gaining a lot of attention in the renewable energy sector in recent years. A large number of offshore wind turbines have been installed recently due to more stable and steady flow of wind and less noise and visual impacts at sea rather than on land (Markard and Petersen 2009; Bilgili et al. 2011). By the end of 2019, the total global installed capacity of offshore wind power was 29.1 gigawatt (GW) (Global Wind Energy Council (GWEC) 2019). Of all the regions in the world, Europe is the leader in offshore wind development and is home for the largest operational wind farms for both fixed-bottom and floating wind turbine technologies. WindEurope (2019) reported the total installed offshore wind capacity of 18,499 MW from 4543 offshore wind turbine units in 11 countries, including the following: United Kingdom, Germany, Denmark, Belgium, Netherlands, Sweden Finland, Ireland, Spain, France and Norway.

Along with increasing wind power generation globally, there will be a substantial number of wind turbines reaching their end-of-life (EOL). In principle, there are three strategies adopted for EOL management of wind farms, which are shown in Fig. 1. These include the following: life extension, repowering and decommissioning (Shafiee and Animah 2017; Ortegon et al. 2013). Life extension involves prolonging the asset lifespan, whereas the repowering involves replacement of the original wind turbines with new and improved wind

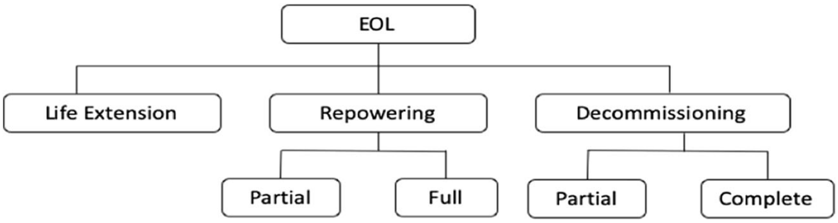


**Fig. 1** End-of-life (EOL) strategies for offshore wind farms (Shafiee and Animah 2017)

turbine components. Decommissioning is the last phase of a wind farm project lifecycle which is applied when other EOL strategies are not feasible (Topham and McMillan 2017; Hou et al. 2017). Decommissioning includes all the activities performed before, during and after dismantling of wind turbines and their supporting assets and equipment. The wind farm assets are disconnected from the grid, dismantled, the items left-in-place are buried or marked, and the site will be returned to its original state (Bezbradica et al. 2016; Rubert et al. 2016; Animah and Shafiee 2018; Ziegler et al. 2018).

The decommissioning process of wind farm assets often depends on several factors such as time to end of leasing permit, age of the fleet, operation and maintenance (O&M) cost of assets and availability of specialised tools. Offshore wind turbine decommissioning is still in its infancy in the world and there are only limited data available in wind energy databases. To date, seven offshore wind farms have been decommissioned and only a few countries have experience of executing decommissioning projects (4C Offshore 2019). Table 1 provides details about the seven offshore wind farms decommissioned in Sweden, UK, Germany, Denmark and the Netherlands. As can be seen, the total decommissioned wind power capacity as at 2019 was 46.45 MW and some of these wind farms were decommissioned before their expected service life.

The amount of decommissioning activities in Europe is anticipated to increase significantly within the next few years, and the wind energy industry will be better off preparing for the financial liability, production deficit in the grid, removal options and strategies and environmental remediation. In order to ensure that decommissioning activities are well managed, the high-cost areas need to be effectively identified and the opportunities and priorities for cost savings to be established in a safe manner. Therefore, the financial implications are the main focus of this study; including the cost and implications of different tasks and activities and the cost of production deficit in the overall energy supply.

Although decommissioning in the wind energy industry is different than that in the oil and gas and nuclear sectors, some lessons can be learned and transferred to the wind energy sector. Accurate estimation of the potential costs to operators and regulators is crucial, so as to make provisions early on in the life of the wind farms and make adequate resource planning. To this aim, the wind energy operators and regulators must design safe and cost-effective decommissioning plans and procedures for assets before they reach the end of their useful life. Attention has to be paid at the early stages of wind farm decommissioning to close the knowledge gap and foster improved procedures and processes in the wind energy industry.

The cost estimation of the entire decommissioning process in offshore wind farms is subject to numerous uncertainties. The estimated cost of decommissioning is usually accounted for at the early developmental stages of an offshore wind farm project, so as to calculate the levelized cost of electricity (LCOE) more accurately. These cost estimates are laden with many assumptions and approximations as there are several factors involved in calculations, such as the project size, project location (water depth and distance from port), decommissioning duration, cost and supply of vessels at the time of decommissioning, type of wind turbines foundation, the cutting and removal equipment, tools and techniques and accumulated skills and experience. Although these estimates make provisions for the initial investment required for decommissioning projects, they often provide a gross underestimate of the actual costs at the time of execution. For a 240 MW wind farm, the decommissioning cost was estimated to account for about 3% of the overall project cost; however, it was concluded that these cost estimates were not true representation of the actual costs (Topham and McMillan 2017).

To date, there has been very limited research about the economic analysis of decommissioning in offshore wind farms in order to identify key cost drivers with respect to different decommissioning activities. To overcome this research gap, we aim to develop an economic assessment framework for decommissioning of offshore wind farms using a cost breakdown structure (CBS) approach. All the cost elements and their key influencing factors are identified from the literature and expert interviews. Similar activities within the decommissioning process are aggregated, and some mathematical models are proposed to estimate the costs associated with activities and identify the most critical cost drivers in each activity group with considering inherent uncertainties. Our framework will provide a clear identification and analysis of factors that influence wind farm decommissioning projects so as to help operators reduce their associated costs. Furthermore, the models ensure that the most critical cost factors are incorporated into the analysis, and major areas of focus for efficient decommissioning project execution and cost savings are identified. A case study of a 500 MW baseline offshore wind farm is proposed to illustrate the models'

**Table 1** Decommissioned offshore wind farms in Europe (4C Offshore 2019)

| Country | Wind farm | Farm capacity | operational years | Decommissioned year | Foundation type |
|---|---|---|---|---|---|
| Denmark | Vindeby | 4.95 MW | 26 | 2017 | Gravity-based |
| Germany | Hooksiel | 5 MW | 9 | 2016 | Tri-pile |
| Netherlands | Lely | 2 MW | 23 | 2016 | Monopile |
| Sweden | Utgrunden I | 10.5 MW | 19 | 2018 | Monopile |
|  | Yttre Stengrund | 10 MW | 15 | 2015 | Monopile |
| UK | Blyth | 4 MW | 13 | 2019 | Monopile |
|  | Beatrice Demonstration | 10 MW | 8 | 2016 | Jacket (piled) |

applicability. The results show that the removal of wind turbines and foundation structures is the most costly and lengthy stage of the decommissioning process due to many requirements involved in carrying out the operations.

The rest of this paper is structured as follows. Section 2 presents an overview of wind farm decommissioning process as well as standards, best practices and strategies that can be adopted in decommissioning activities. Section 3 presents decommissioning cost estimation models and the research studies published in this area. Section 4 describes the decommissioning phases of offshore wind farms and establishes the mathematical relationships between different cost factors by means of process flowcharts. Section 5 proposes a case study applying the cost models to a baseline offshore wind farm project. Section 6 reports the results and discusses the findings. Finally, the concluding remarks and future outlooks on offshore wind energy decommissioning cost estimation are presented in Section 7.

## 2 Overview of decommissioning process in offshore wind

The decommissioning process from an offshore wind farm to another is almost similar; however, it can be tailored on a case-by-case basis and all the factors that are specific to a project can be taken into account, such as the type of wind turbine substructure, water depth, wind turbine capacity and weight. Decommissioning procedures in the UK offshore renewable energy sector are presented in regulatory reports, guidelines and recommended practices. For detailed information about the decommissioning obligations in the UK, the readers can refer to Department for Business, Energy and Industrial Strategy (2019a, b). The decommissioning tasks are often executed by different stakeholders and there must be a coordination of effors to ensure the project is completed on time, within budget and in line with the standards and requirements (Kerkvliet and Polatidis 2016). In the following subsections, the offshore wind farm decommissioning process and relevant strategies, standards, guidelines and recommended practices are briefly reviewed:

### 2.1 Decommissioning activities

Offshore wind farm decommissioning projects are composed of a range of activities from the planning and documentation phase to the site clean-up, surveying and monitoring phase. These activities are all shown in Fig. 2.

The decommissioning activities must be planned for, as much as reasonably practicable, well in advance before the offshore wind farm is commissioned at the initial phase of the project lifecycle. The transportation methods for the removed components during decommissioning should be factored into the engineering design, layout and installation of offshore wind turbines (Castro-Santos 2016). Due to the relatively long time between commissioning and decommissioning of an offshore wind farm, many factors relating to the design and engineering, regulatory compliance, costs, time to decommission and disposal options may change over time, and the models used for the initial estimations must be flexible enough to accommodate such changes. A report by the US Department of Energy (2012) discussed about the environmental impacts of the Cape Wind farm decommissioning activities. Gjødvad and Ibsen (2016) developed a decommissioning process optimisation tool, called ODIN-WIND, to assist stakeholders in offshore wind farm decommissioning projects. The tool is capable of designing appropriate workflows and making changes whenever needed. Topham and McMillan (2017) presented a general decommissioning process breakdown for offshore wind farms and categorised the decommissioning activities into three groups, namely, project management, planning and procurement; operations and post-decommissioning.

Before a wind farm project is approved for commissioning, a plan for all lifecycle phases including the decommissioning phase must be submitted to appropriate regulatory bodies for approval. The decommissioning programme is then revisited and reviewed at regular intervals within the project lifecycle, the last being about 2 years before decommissioning work commences.

### 2.2 Decommissioning strategies

The decommissioning strategy for offshore wind farms is chosen based on a number of financial, safety, socio-economic, environmental and technological factors. The current decommissioning strategies include removal (complete or partial) for reuse, recycling and repurposing (e.g. reef) of the entire wind turbines or the components (Statoil 2014). Partial removal involves removing some components and leaving some others in place like the foundation piles and power cables. However, only certain components can be left in place because of reasons such as excessive cost to decommission and potential environmental impacts. Different removal options, including single lift, piece small or piece large, require different types of vessels and cranes like lifeboats, jack up barges and self-propelled installation vessels (SPIV). Recently, some newer alternatives for wind turbines and foundation removal such as the felling method and float-tow method have also been proposed.

### 2.3 Decommissioning standards, guidelines and recommended practices

The regulatory standards, guidelines and best practices for offshore wind farm decommissioning are based on existing standards from the maritime conventions and other industries such as oil and gas. These include the following:

- Convention on the prevention of marine pollution by dumping of wastes and other matter (London Convention) (1972);
- The United Nations Convention on the Law of the Sea (UNCLOS) (the United Nations 1982);
- Best practicable environmental option (BPEO) (1988);
- International Maritime Organisation (IMO) guidelines and standards for the removal of offshore installations and structures on the continental shelf and in the exclusive economic zone (1989);
- Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention 1992);
- Review of the Current State of Knowledge on the Environmental Impacts of the Location Operation and Removal/Disposal of Offshore Wind-Farms (OSPAR Commission 2006);
- OSPAR Guidance on Environmental Considerations for Offshore Wind Farm Development (2008).

Regional standards, guidelines and best practices are listed as follows:

EU

- Environmental impact assessment (EIA) directive (85/337/EEC)
- Habitats directive (92/43/EEC)

UK

- Decommissioning offshore renewable energy installations (Department of Trade and Industry 2006);
- Decommissioning topic strategy (Health and Safety Executive (HSE) 2001).
- Decommissioning offshore concrete platforms (Health and Safety Executive (HSE) 2003).

USA

- Renewable energy alternate uses of existing facilities on the outer continental shelf (Code of Federal Regulations (CFR) 2011).

## 3 Decommissioning cost estimation

### 3.1 Overview of literature on decommissioning cost estimation

Decommissioning cost estimation includes the quantitative assessment of all the likely costs involved in decommissioning of a project. In offshore wind farms, although the estimated decommissioning costs are accounted for in the application document before any approval is granted at the early stage of the project, this does not present an accurate picture of the true costs at the end of life of the wind farm. This is because cost estimates are subject to many sources of uncertainty. These include the uncertainties about the time that decommissioning activities are anticipated to take place, duration of the decommissioning process, the weather window for execution, options available for decommissioning, etc. Although many government agencies ensure that the decommissioning liability rests on the asset owners, they need to know how much liability they take on. Regulators require asset owners/operators to provide evidence on how they can meet the financial requirements for decommissioning. In order to ensure the financial viability of the decommissioning, the owners/operators much perform an accurate and reliable estimation of the decommissioning costs.

The expected design lifetime of wind turbines is between 20 and 25 years. However, some wind farms may be decommissioned later than the designed lifetime depending on whether their operation is safe and profitable. Many wind farm owners keep their proprietary information about the cost of their decommissioning activities; however, there is no standardised method to incorporate such information in the estimation of total decommissioning costs (Ferrell and DeVuyst 2013). The cost of decommissioning is estimated at the initial phase of the project, and is updated as the project evolves. Decommissioning cost

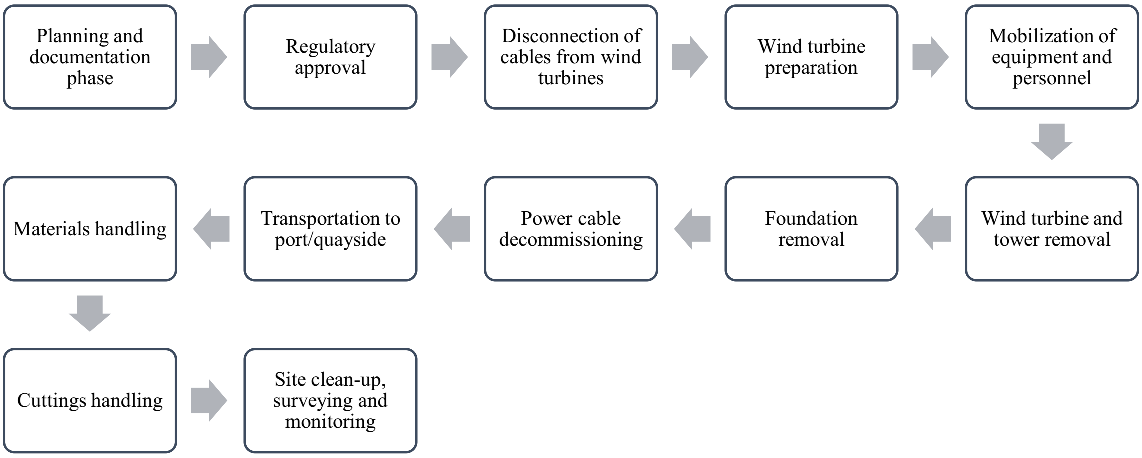


**Fig. 2** Offshore wind farm decommissioning workflow (Gjødvad and Ibsen 2016)

estimation is subject to uncertainties relating to time value of money, changes in assumptions used for cost calculation, changes in demand and supply of resources required for decommissioning, changes in technical and technological methods of decommissioning in the industry, etc.

A number of documents were reviewed for this study to gain a good understanding of the cost drivers in decommissioning of offshore wind farms. The impacts of offshore wind farm decommissioning and some of its cost implications—like the option to remove cables or keep them in place—were discussed briefly in Januário et al. (2007). The studies by Kaiser and Snyder (2010, 2012b) used a bottom-up model to estimate the decommissioning cost of offshore wind farms. The removal costs of wind turbines, foundations, cables, substation and met tower, scour protection, site clearance and material disposal were calculated. However, the costs associated with regulatory approval, insurance and some other costs were neglected in the analysis. A case study was proposed to show the applicability of the models and it was concluded that the decommissioning cost accounted for about 3 to 4% of the CAPEX.

Myhr et al. (2014) assumed that the offshore wind turbines are removed in the reverse of the installation sequence, and therefore, the decommissioning cost was expressed as a proportion of the installation costs. Shafiee et al. (2016) presented a detailed decommissioning cost analysis of fixed-bottom offshore wind farms. In another study by Gjødvad and Ibsen (2016), the offshore wind farm decommissioning cost estimates included different costs associated with activities such as planning and engineering, decommissioning design, contingencies and some other major processes. The study, however, did not present any procedure for cost estimation. Castro-Santos and Diaz-Casas (2014) used a CBS methodology to estimate the lifecycle costs of an offshore floating wind farm. Although the study was not about bottom-fixed wind turbine structures, it captured dismantling costs, which informed some cost elements considered in our study. The total cost of dismantling activity included the port, transportation and removal costs. The study, however, left out overhead costs like planning and regulatory permitting costs, which make up a significant portion of the decommissioning costs. Different criteria for selecting the alternative options for decommissioning methods in offshore wind farms were presented in Kerkvliet and Polatidis (2016). These criteria included economic viability (for both partial and complete removal options), environmental impact and social acceptability. The economic criteria encompassed the removal cost as well as monitoring and maintenance costs of the items left in place.

A more recent publication by Hinzmann et al. (2018) discussed the current methods for decommissioning of fixed-bottom offshore wind farms and proposed some solutions to improve the process. The adoption of these solutions may result in a reduction in decommissioning costs. Another study by Castro-Santos et al. (2018) captured the available lifting methods and installation strategies that may be used during decommissioning for removal, transportation and port handling in offshore deepwater locations. A wind farm decommissioning schedule optimisation model was presented by Irawan et al. (2019) with the aim of reducing the costs. The cost of decommissioning activities in offshore wind farms is heavily influenced by the vessel strategy adopted for removal and transportation of waste material. The optimal strategy is selected based on different criteria, e.g. the type of vessels available from suppliers, type of contract signed for vessel hire (voyage, time or bareboat charter agreements), weather conditions in which the vessel would operate, etc. The type of contract signed for vessel hire would influence the cost of mobilisation, vessel operating costs, fuel, crew, voyage costs, etc.

The waste management methods for decommissioned components in offshore wind farms have been explored in some studies in the literature. All the removed components need to be disposed of according to laws and regulations and in a safe manner. Although steel-made components can be easily recycled, some other components such as blades are difficult in terms of recycling since they are manufactured primarily from composite materials. Disposal of composite materials is difficult due to cost and market restrictions on by-products obtained from recycling of the composite materials. It is often challenging to estimate the benefits associated with recylying of wind turbine components because of changes in materials' salvage value, landfill costs, labour costs, etc. The cost of cutting the recyclable components (e.g. steel) also needs to be weighed against the salvage value (Kaiser and Snyder 2012a). On the other hand, the landfill costs will be dependent on regional landfill tax laws (Pickering 2006; Guezuraga et al. 2012; Cherrington et al. 2012).

The waste management is one of the major factors in environmental impact assessment of the offshore wind farm decommissioning process. However, our review shows that very few studies have focused on environmental footprint reduction of the entire decommissioning process. With potential changes in legislations to reduce the carbon footprints from shipping/marine operations, some of the costs involved in decommissioning may also be impacted. This is because the vessel owners will likely transfer some portion of their costs to asset owners, who will have to pay more than the estimated costs for hiring the vessels. Demir and Taşkin (2013) studied the environmental impact of wind turbines throughout their lifetime using a Lifecycle Cost Analysis (LCA) approach. The analysis focused on two phases, namely, (i) manufacturing and operation, and (ii) decommissioning and recycling. The authors assumed that only 90% of steel were recycled and the other 10% of metals were landfilled.

### 3.2 Decommissioning cost estimation techniques

There are several cost estimation tools and techniques which can be adopted in the decommissioning process. These include expert judgement, analogous estimating, parametric modelling, bottom-up analysis, three-point estimating, data analysis, project management information system and decision making by voting (Project Management Institute 2017). A study by ARUP for the UK's Department for Business, Energy and Industrial Strategy (2018) presented a framework to predict the total cost of offshore wind decommissioning. Some of the cost factors identified in the study include: number of workboats needed for removal, execution time and number of turbines to be removed. In another study by Topham and McMillan (2017), a decommissioning process breakdown structure was proposed and the duration and cost for decommissioning activities were estimated. The study considered the removal of only wind turbines and their foundations and the transmission assets were excluded from the analysis. Also, the overhead costs (planning and regulatory approval costs), waste management and post-decommissioning costs were neglected. The study focused on determining an optimal approach for transporting the removed components by the use of only removal vessels or a combination of removal and transport vessels. It was concluded that using two vessels simultaneously would result in the most cost-effective transportation system for the wind farm decommissioning.

In the Shafiee et al. (2016) and Kaiser and Snyder (2010, 2012b) studies, the lifecycle cost analyses were performed, accounting for costs that are incurred during the decommissioning phase. Shafiee et al. (2016) addressed the primary cost elements, including the port rental, removal, waste management, site clearance and post-decommissioning costs. Kaiser and Snyder (2012b) used an empirical approach to estimate the cost of decommissioning for offshore wind farm projects. The study detailed cost models for removal of wind turbines and support structures, cables, substation and met tower, scour protection, site clearance and disposal (based on salvage value, processing, landfill and transport costs). Each cost element was estimated using different case studies; however, no case study was used to estimate the expected planning and regulatory approval cost or work contingencies such as equipment breakdown. The authors conclude that the decommissioning cost estimation is still fundamentally uncertain.

## 4 The proposed framework

In this section, a cost-breakdown structure (CBS) is developed for decommissioning of offshore wind farms. To this aim, a work breakdown structure (WBS) is presented to identify the major cost drivers during decommissioning execution in a systematic manner. The main difference between cost estimation of a decommissioning project and that of other engineering construction projects is that decommissioning is not primarily intended for profitability. Thus, much attention must be paid to ensure safety while minimising the decommissioning cost. Therefore, our analysis will be useful not only to identify and analyse the cost elements involved in decommissioning process of offshore wind farms but also to provide solutions on how to reduce cost of decommissioning activities.

The proposed framework covers all phases within the decommissioning process that contribute to the total decommissioning cost estimate. The costs can be either direct or indirect, fixed or variable. Direct costs are those accrued as a direct result of the activities or tasks performed, whereas indirect costs arise from other overhead expenditures necessary to support decommissioning activities. Fixed costs are those that remain unchanged regardless of amendments during the project execution, whereas variable costs are flexible and change with the level of activity. The major cost drivers can also be updated in our framework so as to take into account the changes in decommissioning cost factors at the time of project execution.

The CBS developed for the decommissioning of offshore wind farms is represented in Fig. 3. As can be seen, the wind farm decommissioning process is divided into four primary phases, namely planning and regulatory approval, execution, logistics and waste management and post-decommissioning. These phases are broken down further into several subtasks, and then, the cost information of phases and subtasks are used to estimate the total decommissioning cost ($C_{\text{decom}-\text{total}}$). Therefore,

$$C_{\text{decom}-\text{total}} = \sum C_{P\&RC} + \sum C_{EX} + \sum C_{Lo\&WM} + \sum C_{P-\text{Decomm}} \tag{1}$$

where $C_{P\,\&\,RC}$ , $C_{EX}$, $C_{Lo\,\&\,WM}$ and $C_{P\,-\,\text{Decomm}}$ represent the planning and regulatory approval cost, execution cost, logistics and waste management cost and post-decommissioning cost.

As the execution of an offshore wind farm decommissioning project may take some time, the net present value (NPV) method is used to incorporate the time value of money. The NPV equation is expressed as follows:

$$\text{NPV} = \sum_{t=0}^{T} \frac{R(t)}{(1+r)^t} \tag{2}$$

where $R(t)$ is the net cash flow of the decommissioning project in a given year $t$, $r(>0)$ is the discount rate and $T$ is the duration to complete the decommissioning project. In what follows, the decommissioning phases are explained:

## 4.1 Planning and regulatory approval phase

The planning and regulatory approval phase consists of three subtasks, namely, engineering planning and project management, regulatory approval and contingency planning.

### 4.1.1 Engineering planning and project management

Engineering planning involves organisation of all the leasing, technical, purchase and contractual requirements for an offshore wind farm decommissioning project. Project management is required throughout the duration of the decommissioning process so as to make sure all project tasks are on schedule and the milestones are met. Provisions for engineering planning and project management are critical as the risks posed by the project execution may be identified and duly addressed, contracts agreed, tasks scheduled and costs assigned to all stakeholders. Engineering planning also involves performing environmental risk assessments and identifying risk responses required during execution of the project (Statoil 2014). Since a decommissioning project involves inputs from different contractors, suppliers and vendors, the project team ensures that all tasks are well managed for delivery. The project management plans for the scope, resources, cost, schedule, quality and risk are inputted into the cost estimations and then used to update the project documents. The contracts for different work phases and equipment and vessel hires have to be accounted for.

In many cases, the project management cost ($C_{PM}$) is calculated as a percentage of the total decommissioning cost. Therefore,

$$C_{PM} = \beta^* C_{\text{decom}-\text{total}} \tag{3}$$

where $\beta > 0$ is the percentage of planning and project management cost from total decommissioning cost. In this study, $\beta$ is assumed to be 6%; however, it may be subject to changes depending on market conditions (Statoil 2014).

### 4.1.2 Regulatory approval

There are a number of guidelines related to decommissioning activities in the renewables sector at both national and international levels. However, only a few of these regulations refer to offshore marine installations in general. In a study by Smyth et al. (2015), a regulatory framework for different decommissioning options in the offshore wind power industry is presented. In the UK, the Department for Business, Energy and Industrial Strategy (2019a, 2019b) published guidance notes for the decommissioning of offshore wind structures. These guidelines clearly spell out the responsible parties for wind farm asset decommissioning and describe a seven-stage process to obtain the regulatory approval for a decommissioning project. It is recommended that decommissioning discussions begin at the initial planning and consenting stage for installation during which the programme draft and the environmental impact assessment are submitted to the Secretary of State. Inputs from all stakeholders are necessary at this stage so as to avoid problems during the decommissioning execution phase. The stakeholders include the fishing industry and other sea users, the maritime and coast guard agency and environmental protection agencies. Notifications must be made to other agencies like the mariners and fishermen's organisations to inform them of the upcoming decommissioning activities and to receive their inputs. All necessary permits for use of the sea will need to be processed for all the activities planned. Regulatory approval applications for decommissioning campaigns vary from region to region, but they must include details about the assets to be decommissioned, the proposed schedules for different activities, removal techniques and procedures, resources required, an environmental impact assessment and a list of assumptions made in all work schedules, safety and cost estimates. If the decommissioning approval is not granted by the regulator, some revisions will need to be made before resubmission of

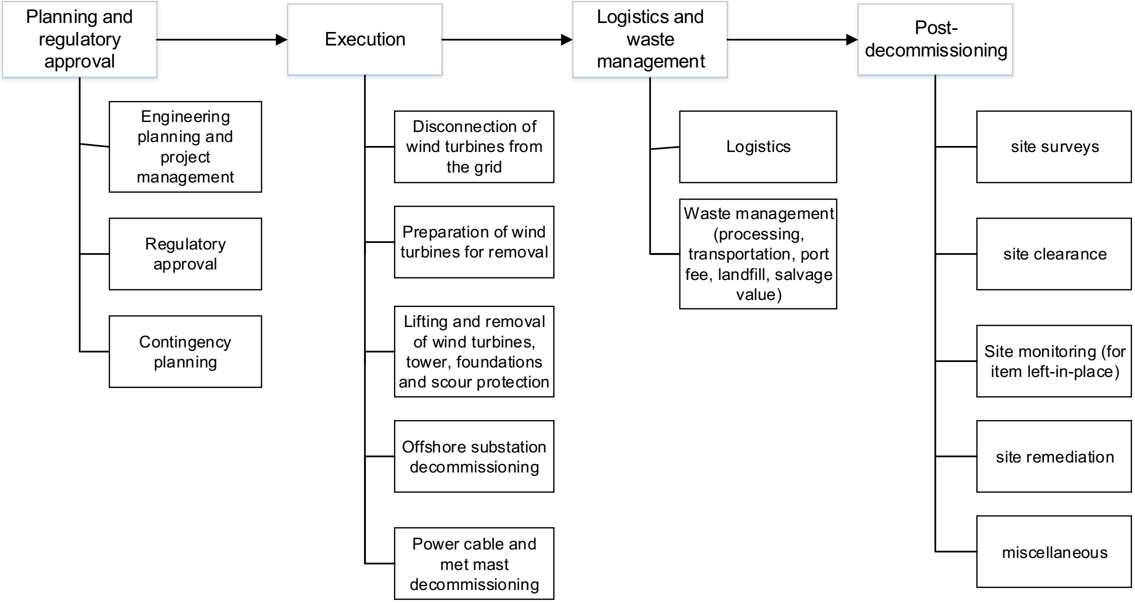


**Fig. 3** Cost breakdown structure (CBS) for decommissioning activities in offshore wind farms

the documents. Appendix Fig. 10 illustrates a flowchart for planning and regulatory approval of offshore wind farm decommissioning projects.

Currently, no regulatory approval fee is paid for wind farm asset decommissioning in the UK; however, it may change in the future (Department for Business, Energy and Industrial Strategy 2019b). Using the oil and gas fee structure, it is assumed that wind farm decommissioning fees are structured in either of the following forms:

$$C_{RA} = (K{*}N_{WT}) + C_{\mathrm{revision}} \tag{4}$$

$$C_{RA} = (K{*}A_{WT}) + C_{\mathrm{revision}} \tag{5}$$

where $C_{RA}$ and $C_{\mathrm{revision}}$ represent the costs of regulatory approval and revising the decommissioning plan, respectively. $K$ is a constant, $N_{WT}$ is the number of wind turbines or the wind farm capacity and $A_{WF}$ is the area of the wind farm.

### 4.1.3 Contingency planning

Contingency planning is required to allow for making changes in the schedule or any additional work that was not previously accounted for. As wind farm operators and contractors become more experienced, less contingency allocations may be required due to some reduced uncertainty. It may be grouped into work contingencies and wait-on-weather (WoW) to make allowances in the event of changes in vessel spread costs, workflow modifications and bad weather conditions. The work contingencies usually make up about 10% of total decommissioning cost, depending on the type of wind turbines and the distance from shore. The WoW makes up around 20% of the total decommissioning cost. Thus, the contingency cost is estimated to range between 10 and 30% of the total decommissioning cost (Statoil 2014; Kaiser and Liu 2015). In this study, the contingency cost is expressed as follows:

$$C_{\mathrm{conting}} = \alpha \times C_{\mathrm{decom-total}} \tag{6}$$

where $\alpha$ represents the percentage of WoW and other work contingencies related to schedule changes and unplanned works.

The total cost of engineering planning and project management phase is given by:

$$\begin{aligned}\sum C_{P\&RC} = {} & C_{E\text{-}\mathrm{plan}} + C_{PM} + C_{\mathrm{conting}} + C_{\mathrm{consult}} + C_{\mathrm{audit}} \\ & + C_{EIA\text{-}\mathrm{survey}} + C_{\mathrm{amend}} + C_{RA} + C_{\mathrm{permit}} \\ & + C_{\mathrm{insure}}\end{aligned} \tag{7}$$

where $C_{E-\mathrm{plan}}$, $C_{\mathrm{conting.}}$, $C_{\mathrm{consult}}$, $C_{\mathrm{audit}}$, $C_{EIA-\mathrm{survey}}$, $C_{\mathrm{amend.}}$, $C_{RA}$, $C_{\mathrm{permit}}$ and $C_{\mathrm{insure}}$ represent the costs associated with engineering planning, contingency, consultation, facility audit, environmental impact assessment survey, amendment expenses, regulatory approval, permit and insurance, respectively.

## 4.2 Execution phase

When the decommissioning plan is approved and all contractual and legal documentations are signed, the decommissioning execution will start. Project management will be ongoing throughout this stage to ensure that tasks are completed to budget, schedule and quality. The contingency plan and budget will also be continuously revisited at different milestones during the execution phase. Some activities are spaced out months apart, depending on the schedule and availability of removal facilities. A flowchart for the execution phase of offshore wind farm decommissioning projects is shown in Appendix Fig. 11.

The cost of decommissioning execution is equal to summation of the cost of activities involved. Therefore,

$$C_{EX} = C_{\text{disc}} + C_{\text{prep}} + C_{L\&R} + C_{\text{OSS-decom}} + C_{\text{cable decom}} \quad (8)$$

where $C_{\text{disc}}$, $C_{\text{prep}}$, $C_{L\,\&\,R}$, $C_{\text{OSS}-\text{decom}}$ and $C_{\text{cable decom}}$ represent the cost of disconnection of wind turbines from the grid, cost of wind turbine preparation for removal, cost of lifting and removal of wind turbines, tower, foundations and scour protection, cost of decommissioning of offshore substations and cost of decommissioning of cables (inter-array and export), respectively. These costs are explained in details in the sections below.

### 4.2.1 Disconnection of wind turbines from the grid

Disconnection of wind turbines from the grid is the first activity in the decommissioning execution phase. It ensures that transmission of power from the wind turbines to the substation is stopped, the turbines are de-energised and electrically isolated and the inter-array cables are disconnected. This task involves costs of personnel and workboat.

### 4.2.2 Preparation of wind turbines for removal

The wind turbines are prepared for removal by extracting lubricating fluids and other harmful materials from the nacelle. This waste will be transported to shore for adequate handling to specified standards. The activities are carried out in a way as to make the removal process as safe as possible. Other preparation activities include rotor reorientation, ventilation of airtight platform, removal of the elevator in the tower, removal of marine growth on the foundation structures or anti-scour mattresses, draining the offshore substation platform (OSP) (of oils or resins) and fitting/welding lift point fixtures (onto the monopile, OSP topsides and masts) and installation of navigational lights and markings in order to ensure that obstructions during and after decommissioning are visible to prevent navigational hazards (Statoil 2014; Topham and McMillan 2017). The cost of preparation of wind turbines for removal is given by:

$$\begin{aligned} C_{\text{prep}} = \; & \left(N_i {*} C_{i/\text{day}} \times t_{\text{prep}}\right) + \left(C_{\text{fixt/unit}} \times N_{\text{fixt}}\right) \\ & + \left(N_k \times C_{k/\text{day}} \times t_{\text{prep}}\right) + C_{\text{Nav-mark}} + C_{\text{eqt/day}} \end{aligned} \quad (9)$$

where $N_i$ is the number of vessels required from type $i$ (where $i = 1$: workboat, $i = 2$: jack up, $i = 3$: helicopter, $i = 4$: other vessels such as heavy lift vessels (HLV), offshore support vehicles (OSV), barges, etc. (GL Garrad Hassan 2013), $C_{i/\text{day}}$ is the daily rental rate of a vessel from type $i$, $t_{\text{prep}}$ is the time taken to complete all tasks such as draining the lubricating fluids ($t_{WT-\text{drain}}$), marine growth removal ($t_{MG-\text{remov.}}$), offshore substation draining ($t_{OSS-\text{drain}}$) and the pre-decommissioning survey ($t_{\text{pre}-\text{survey}}$), $C_{\text{fixt/unit}}$ is the cost per fixture unit required for lifting wind turbines and support structures, $N_{\text{fixt}}$ is the number of fixtures, $N_k$ is the number of personnel, $C_{k/\text{day}}$ is the labour cost per day, $C_{\text{Nav}-\text{mark}}$ is the cost of navigation markings (similar to installation) and $C_{\text{eqt/day}}$ is the equipment cost per day.

### 4.2.3 Lifting and removal of wind turbines, tower, foundations and scour protection

The removal of wind turbines includes cutting and lifting of all the components such as blades, hub, nacelle, tower, support structure, foundation and cables. The disassembly of these components and deconstruction of transition pieces require different types of vessels with different capacities. The type of vessel is often determined based on the transportation strategy which itself is a function of the removal option, distance to port ($D_{\text{port}}$), number of lifts ($N_{\text{lifts}}$), estimated total weight ($W_{\text{total}}$), weight per lift ($W_{\text{lift}}$), vessel capacity required ($V_{\text{capacity}}$), number of vessels required ($N_V$), number and duration of trips to and from port including loading and offloading time ($N_\gamma$and $t_\gamma$) and activity durations ($t_j$). The lifting and removal vessel and equipment cost are based on fixed vessel rental costs and daily hire rates ($C_{i/\text{day}}$) and the abovementioned cost functions. The types of vessel used for removal of wind turbines include tug boats, lift barges, mechanical dredges, HLV, OSV, jack up vessels and SPIVs (Uraz 2011).

Cutting methods include internal or external abrasive water jetting, oxy-flame cutting, diamond wire cutting, explosives, laser cutting and "felling" of the wind turbine structures by using internal or external cutting methods (which reduce or remove the need for a specialised vessel). There are also different lifting and removal options that can be adopted from the wind turbine installation methods such as the bunny ear and tower in one piece and hub and tower in one piece (see Kaiser and Snyder 2012a; Gjødvad and Ibsen 2016; Paterson et al. 2018; Castro-Santos et al. 2018). The total lifting and removal cost of wind turbines are calculated by the following equation:

$$\begin{aligned} C_{L\&R} = \; & \left(N_i \times C_{i/\text{day}} \times t_j\right) + \left(N_\gamma \times C_{i/\text{day}} \times t_\gamma\right) \\ & + \left(N_k \times C_{k/\text{day}} \times t_j\right) \end{aligned} \quad (10)$$

where $N_i$ is the number of vessels required from type $i$, $t_j$ is the time needed to complete all subtasks, $N_\gamma$ is the number of trips required to shore and $t_\gamma$ is the distance to and from shore. The time required to complete all lifting and removal tasks ($t_j$) is given by Eq. (11):

$$t_j = t_{L\&R\text{–}WTG} + t_{L\&R\text{–}B\&N} + t_{L\&R\text{–}T\&TP} + t_{L\&R\text{–found}} + t_{\text{cable–decom}} + t_{L\&R\text{–misc}} \tag{11}$$

where $t_{L\,\&\,R-WTG}$ is the time required for lifting and removal of wind turbines, $t_{L\,\&\,R-B\,\&\,N}$ is the time required for blades and nacelle removal, $t_{L\,\&\,R-T\,\&\,TP}$ is the time required for tower and transition piece removal, $t_{L\,\&\,R-\text{found}}$ is the time required for foundation removal, $t_{\text{cable}-\text{decom}}$ is the time required for decommissioning of inter-array and export cables and $t_{L\,\&\,R-\text{misc}}$ is the time required for lifting and removal of miscellaneous components such as concrete mattresses, scour protection and rocks. Some tasks can be divided into further subtasks. For example, $t_{L\,\&\,R-WTG}$, $t_{L\,\&\,R-B\,\&\,N}$ and $t_{L\,\&\,R-T\,\&\,TP}$ involve time to set-up, lift, jack down (if jack-up is used) and move to another wind turbine. $t_{L\,\&\,R-\text{found}}$ involves time to stabilise, pump, cut and lift foundation and move to another foundation.

The type of wind turbine foundation is a major consideration when planning the removal activities. There are different types of foundation in offshore wind farms. These include fixed-bottom (such as gravity-based, monopile, tripod and jacket) and floating (such as spar-buoy, tension-leg and semi-submersibles). The type and weight of foundation are usually correlated with the water depth and will determine whether the foundation needs to be completely or partially removed. A flowchart for the foundation removal activity in offshore wind farm decommissioning projects is shown in Appendix Fig. 12. The fixed-bottom structures must be cut to the regulatory-required depth (15 ft), whereas the floating foundations are detached from the mooring lines (which attach them to the seabed) and transported to the shore. Gjødvad and Ibsen (2016) introduce different removal methods for wind turbine foundations. These methods include cut-lift-carry (CLC), lift-float-tow (LFT) and detach-tow (DT). Monopiles are mostly removed partially, using jack-up (JU) barges or HLVs and cranes for lifting and removal operations and tow boats for transportation. For complete removal, dredging vessels may be required. A list of removal options and methods for different types of wind turbine foundations is given in Table 2.

### 4.2.4 Offshore substation decommissioning

The substation is the collection point of the power generated from a wind farm before it is transferred to the grid. Offshore substation decommissioning includes the removal of the topsides and foundation and the transportation of the modules to the port. A list of offshore substation components to be decommissioned is provided in the Diamond Transmission Partners BBE Limited document (2018). Appendix Fig. 13 also shows a flowchart for the substation removal activity in offshore wind farm decommissioning projects. The factors affecting the cost of substation decommissioning include the vessel requirements, water depth, distance to port, pile diameter and wall thickness, duration of the removal activity and need for navigational markings during decommissioning. The OSP foundation pile is decommissioned in a similar way to the wind turbine foundation and is cut below the seabed level to ensure it causes no obstructions for other users of the sea. Markings must be put in place and communicated to other sea users via the most appropriate and relevant channels in order not to pose any risk. Greater Gabbard Offshore Winds Limited (2007) listed a number of criteria used to decide whether to completely or partially remove the offshore substations. These include the following: safety, other sea user needs, environmental impact, sustainable development, polluter-pays principle, reuse maximisation, commercial viability and practical integrity.

The total offshore substation decommissioning cost is calculated by Eq. (12):

$$C_{\text{OSS–decom}} = \left(N_i \times C_{\frac{i}{\text{day}}} \times t_{\text{OSS–decom}}\right) + \left(C_{\frac{i}{\text{day}}} \times t_\gamma \times N_\gamma\right), \tag{12}$$

where all parameters are similar to that of the wind turbines but specific to the removal of offshore substation.

### 4.2.5 Power cable and meteorological mast decommissioning

The power cables (including inter-array and export cables) are either completely removed or decommissioned in-place by burial to a specified depth. In more recent installations, the cables are very well arranged in wind farm layouts; therefore, mapping the cable locations on the seabed is fairly straightforward. Cable installation requires some self-propelled vessels, barge-tug systems, OSVs and cable-laying vessels equipped with remotely operated vehicles (ROVs) (Kaiser and Snyder 2010). These vessels and equipment can also be used for cable decommissioning purposes. However, this will be determined based on whether the decommissioning option is partial or complete. The regulatory standards to date do not require all cables to be removed, and most of the cables are simply buried below the seabed level. If cables are removed, then the waste management method will be recycling, as there is a relatively ready market for copper recycled from long-distance cables. When they are left in situ, they may be reconnected for reenergising if the seabed soil settles and can be reused.

The factors affecting the total cost of cable decommissioning include the following: time, vessel day rate, equipment day rate, transportation strategy, removal option, time, intra-field movement time, weather window, vessel capacity, speed, water depth, distance to port and removal/burial rate. The vessel day rates may include the cost of ROV equipment if this is hired from an independent contractor. It is difficult to accurately estimate the cable removal rates as there is little data publicly available. Kaiser and Snyder (2012b) presented an approach to estimate the cable removal rates by adjusting the installation rates. Their technique would be useful when there is a limited data, but the results must be reviewed as more data becomes available. Based on the installation data, the cable length during removal will be known. Hence, some uncertainty is eliminated regarding the length and the reeling equipment that may be required. The capacity of vessel storage, winch, ROV and hydraulic sheer equipment can also be determined. If the cables are cut and buried, mattresses or concrete covers/rocks may be used to cover the cable ends (Kaiser and Snyder 2010).

The most cost-effective option for both the inter-array and export cables is to bury and monitor them in perpetuity. In the case where the cables are not cut but buried, the decommissioning cost will be estimated by Eq. (13):

$$\begin{aligned} C_{\text{cable-decom}} = & \left(N_i \times C_{\frac{i}{\text{day}}} \times t_{\text{cable-decom}}\right) \\ & + \left(N_\gamma \times C_{\frac{i}{\text{day}}} \times t_\gamma\right) \\ & + \left(N_k \times C_{\frac{k}{\text{day}}} \times t_{\text{cable-decom}}\right) + C_{\text{eqt/day}} \end{aligned} \quad (13)$$

where $C_{\text{cable-decom}}$, $N_i$, $C_{i/\text{day}}$, $t_{\text{cable-decom}}$, $N_\gamma$, $C_{i/\text{day}}$, $t_\gamma$, $N_k$, $C_{k/\text{day}}$ and $C_{\text{eqt/day}}$ represent the cost of cable decommissioning, number of vessels from type $i$ required for cable removal, cost of removal vessels per day, time required for cable decommissioning, number of trips to and from shore, cost of transportation vessels per day, time for transportation to and from shore, number of personnel, cost of personnel per day and the cost of equipment per day, respectively.

The workflow of cable decommissioning process depends mostly on the decommissioning option which is selected based on financial, environmental, risk, technical and social factors. A flowchart for the cable decommissioning in offshore wind farms is shown in Appendix Fig. 14. The duration of cable decommissioning depends on the time to cut, de-bury and reel cables onto the ship. The safety/risk factors include any potential interference to other marine activities by other users. The masts (meteorological towers) are often put in place for signalling transmission and notifying other sea users about the installations in place.

## 4.3 Logistics and waste management phase

Depending on the removal option adopted for offshore wind farm installations, the removed components will be transported to a port where some preparations are carried out for component reuse, recycling, incineration or scrapping (e.g. disposal in a landfill). The components may be sorted into different categories, for example, metals (aluminium, steel, copper from cables, etc.), electrical components, mechanical components, hydraulic waste and concrete waste. This systematic approach makes it possible to manage all components economically, safely and environmentally. The main inventories during offshore wind farm decommissioning projects include steel, concrete, plastic, non-ferrous (e.g. carbon fibre, concrete), drill cuttings and hazardous substances. Each inventory must have a pre-approved mode of transportation and disposal. The costs incurred in this phase include logistics cost ($C_{\text{logistics}}$) and waste management cost ($C_{WM}$). Therefore,

$$C_{Lo\&WM} = C_{\text{logistics}} + C_{WM} \quad (14)$$

Since logistics costs are market-sensitive, their estimation will be subject to uncertainty until it is closer to the time when the decommissioning project starts.

### 4.3.1 Logistics

Logistics planning is critical to the success of offshore wind farm decommissioning projects. It involves movement/transportation, storage and processing of material throughout the decommissioning process (Shafiee 2015). Movement/transportation of resources during the decommissioning process is a financial, technical, organisational and safety critical challenge. Lange et al. (2012) argued that there is a need for the wind energy industry to embed their logistical processes within the maritime supply chain requirements. The need to do this will become more urgent in the coming years as the number of wind farm assets approaching their end of life is increasing. The authors proposed a campaign-based supply chain simulator for the wind energy industry that can be used for logistics service providers. Sarker and Faiz (2017) assumed that the total duration for transportation is a function of the wind turbine's rated power output and the pre-assembly method. The authors performed a sensitivity analysis to investigate the effect of increasing experience on transportation and installation costs. Topham and McMillan (2017) proposed a model to estimate the time and cost per MW for different transportation strategies in order to select the most cost-effective and time-optimal strategy.

The contract signed with a vessel supplier is usually based on a fixed daily rate or turnkey contract when the vessels are to be hired. The same vessel can be used to remove, store and transport the components to the port. Different transportation strategies can be adopted, including self-transportation/pendulum strategy, barge method and multi-vessel/collector method (Lange et al. 2012; Kaiser and Snyder 2012b). The self-transportation/pendulum strategy involves using the same vessel for wind turbine removal and transportation to shore and back

**Table 2** Removal options and methods for different types of wind turbine foundations (Ontario Ministry of the Environment and Climate Change 2016)

| Type of foundation | Typical removal option | Removal method |
|---|---|---|
| Monopile | Partial/complete | CLC/LFT |
| Tripod | Partial/complete | - |
| Jacket | Partial/complete | CLC |
| Suction bucket | - | LFT |
| Gravity-based | Complete | LFT |
| Floating | Complete | DT |

to the site. This will only be cost-effective for a small-scale wind farm. The barge method and multi-vessel/collector method involve using a vessel for removal and another vessel for transportation to the shore. The type of vessel used depends on the cutting method, transportation method, the size and number of components and water depth. The types of vessels that may be hired include the following: tugs, barges, lift vessel, mechanical dredges, JU vessels, removal vessels, SPIV, OSVs, heavy-lift vessel and clean-up vessels.

Logistics software tools such as ODIN-WIND can be useful to determine the number and types of vessels required for lifting and removal of wind turbines (Gjødvad and Ibsen 2016). The factors influencing the logistics costs include the following: distance to and from port, port fees, port capacity, port upscale requirement, storage and processing capacity of port, permit durations, mobilisation/demobilisation costs (vessels and personnel), water depth, number of vessels, number of personnel/crew, accommodation and feeding costs, duration of activities, number of vessels required (and different vessel class mixes), selected transportation strategy, weather windows (uptime and downtime), vessel capacity and weight and dimensions of the items to be transported, crane capacity and probability of failure of equipment/vessels and the duration of replacement. (Kaiser and Snyder 2012a; Lange et al. 2012; Topham and McMillan 2017; Sarkar and Faiz, 2017; Gjødvad and Ibsen 2016). A flowchart for logistics planning of the decommissioning process in offshore wind farms is shown in Appendix Fig. 15.

The cost of vessels has been accounted for in different execution activities for ease of calculation; hence, that is left out in this subsection to avoid double counting. The logistics cost can be expressed as:

$$C_{\text{logistics}} = \left(N_i \times C_{i/\text{day}} \times t_j\right) + \left(N_k \times C_{k/\text{day}} \times t_j\right) + \left(C_{i/\text{day}} \times t_\gamma \times N_\gamma\right) + C_{\text{accom}} + C_{\text{port/annum}} \quad (15)$$

where $N_i$, $C_{i/\text{day}}$, $t_j$, $N_k$, $C_{k/\text{day}}$, $C_{\text{accom}}$ and $C_{\text{port/annum}}$ represent the number of vessels from type $i$, daily rate of each vessel, the time required for decommissioning execution, number of personnel, labour cost per day, accommodation cost and port rental fee per day, respectively.

### 4.3.2 Waste management

With the increasing number of offshore wind installations, more and more waste materials are produced (Liu and Barlow 2017; Sudaia et al. 2018; Jensen 2019). Many regulations across several regions prohibit the disposal of wastes in the sea and require adequate sustainable practices for disposal onshore. The waste management methods include waste handling processes adopted at the final stage of decommissioning activities where the recovered components reach the end of their lifetime. The materials handling methods include reuse, recycling, repurposing (e.g. as artificial reefs), refining and hazardous materials handling, mechanical processing, incineration for energy recovery and disposal to landfills. (Kaiser and Snyder 2012a; Gjødvad and Ibsen 2016; Jensen 2019). After unloading at the port, the components have to be separated, sorted, cut, crushed or packaged for transfer for further processing. A flowchart for waste management in offshore wind farm decommissioning project is shown in Appendix Fig. 16.

Studies report that some wind turbine components such as blades are either challenging to recycle or have little salvage value. Their recyclability, therefore, requires more research compared with other components. The most practical method of waste management for blades is energy recovery through incineration. Some non-recyclable wastes include lubricants and coolants, power electronics and composite materials (Januário et al. 2007; Cherrington et al. 2012; Topham et al. 2019). The waste management methods for different wind turbine components are presented in Table 3.

The cost of waste management is dependent on the port location, labour and local transportation costs (Cherrington et al. 2012). In this study, the cost of waste management is given by (Shafiee et al. 2016):

$$C_{WM} = C_{w\text{–proc}} + C_{w\text{–OTransp}} + C_{\text{port}} + C_{\text{landfill}} - SV, \quad (16)$$

$$C_{w\text{–proc}} = C_{{}^{w\text{–proc}}\!/_{\text{unit}} \times Wt_j}, \quad (17)$$

$$C_{w\text{–OTransp}} = C_{\text{truck/km}} \times \left[\frac{\sum Wt_j}{W_{\text{truck}}}\right] \times t_\gamma \times N_\gamma, \quad (18)$$

where $C_{w-\text{proc}}$ is the waste processing cost, $C_{w-\text{OTransp}}$ is the onshore waste transportation cost, $C_{\text{port}}$ is the port fees, $C_{\text{landfill}}$ is the landfill costs, $SV$ is the salvage value, $C_{{}^{w\text{–proc}}\!/_{\text{unit}}}$ is the cost of waste processing per unit material, $Wt_j$ is the weight of recyclable and non-recyclable materials, $C_{\text{truck/km}}$ is cost per kilometre for a truck, $W_{\text{truck}}$ is the capacity of a truck, $t_\gamma$ is the total time for transportation and $N_\gamma$ is the number of trips. The recyclable materials include all the materials that are not disposed of in the landfill. All recyclable materials will be managed in a way so as to maximise their salvage value. The salvage value for recyclable materials is calculated by Shafiee et al. (2016):

$$SV = \sum {W_j}^R \times SV_{\text{per unit wt}}, \tag{19}$$

where ${W_j}^R$ is the weight of recyclable materials and $SV_{\text{per unit wt}}$ is the salvage value per unit material.

### 4.4 Post-decommissioning phase

Post-decommissioning is the last phase of offshore wind farm decommissioning projects. This phase consists of all activities carried out to ensure that the site condition is returned, as much as is possible, to its original state. This involves perpetual monitoring and management of the offshore wind site. During the post-decommissioning phase, the seabed soil will be allowed to settle naturally. Also, any items left-in-place (e.g. buried cable ends and pile ends) will be monitored in perpetuity. A flowchart for post-decommissioning of offshore wind farms is shown in Appendix Fig. 17.

There are several factors affecting the cost of post-decommissioning. For example, the distance from shore is a critical factor for the logistics related activities/tasks. Other factors like length of mooring lines, size of anchors and length of cables also need to be considered. In general, the post-decommissioning costs are divided into cost of surveying, cost of cleaning up the site and cost of hiring vessels, personnel/crew and equipment. It is difficult to quantify the cost of post-decommissioning monitoring as it is dependent on the types and number of items left in place. This becomes a liability of the government if the former operator goes out of business, or the liability is not transferred to the new business owner if sold. Other activities that are categorised under miscellaneous include notifying the appropriate bodies for map updates within the regulatory requested period. In the UK, the Hydrographic Office (https://www.admiralty.co.uk/) must be notified at least 6 months before any map is updated.

The cost of post-decommissioning ($C_{P-\text{Decomm}}$) is calculated by the following equation:

$$C_{P\text{–Decomm}} = C_{\text{surv}} + C_{Sc} + C_{Sm} + C_{\text{rem}} + C_{\text{misc}} \quad , \tag{20}$$

where $C_{\text{surv}}$, $C_{Sc}$, $C_{Sm}$, $C_{\text{rem}}$ and $C_{\text{misc}}$ represent the costs of site survey, site clearance, site monitoring, site remediation (if required) and miscellaneous, respectively.

## 5 Case study

In this section, the proposed decommissioning cost estimation models are tested on a 500 MW baseline offshore wind farm. This baseline case has been studied in some studies in the past (e.g. see Castro-Santos and Diaz-Casas 2014; Myhr et al. 2014; Shafiee et al. 2016). The water depth at the wind farm site ranges between 30 and 45 m. The type of foundation suitable for such water depth is a jacket structure. The method for foundation removal is cut-lift-carry (CLC). During the decommissioning process, all the wind turbines are removed and the jacket foundations are cut 15 ft below the seabed. The wind farm has one offshore substation. The export cables are assumed to be left in place at the end of the life of the project. It is assumed that different removal vessel classes and barges are used for the decommissioning operations. However, the capacity of the vessels remains unchanged throughout the process.

### 5.1 Planning and regulatory approval phase cost

The costs for the planning and regulatory phase are calculated based on the current UK legislation. The planning and regulatory approval cost is made up of the engineering planning base cost, legal permit cost, environmental impact assessment cost, facilities audit cost, consultation, contractor and vendor fees, insurance premiums and contingency planning costs.

### 5.2 Execution phase cost

The cost of decommissioning execution includes the costs associated with lifting and removal of wind turbines, foundations, inter-array cables, offshore substation and met masts. The inputs required to estimate the cost of decommissioning execution include the type and number of vessels used, the number and time of trips to shore and cost of transportation spread, and the number and cost of offshore personnel and the time required for the removal activity. It is assumed that there is a transportation spread available at the time of removal for transportation to shore. The WoW is accounted for the time needed to complete each activity. The time taken to remove jacket foundations is assumed to be 80% of their installation time, whereas the time for wind turbines removal is 90% of installation time. The typical vessels used for wind turbines and foundations removal are jack up and HLVs. The daily rate of jack up vessels is £149,800/day, whereas the daily rate of HLVs is £288,900/day, inclusive of fuel costs. Based on the vessel day rates, the total lifting and removal cost of the wind turbines and their foundations will range between £81.72 and £157.31 million. Crew boats are estimated to be on site and the selected modes of transportation for the removed components are barges and tugboats. The number of barges, tugs and crew boats may vary, and the optimal number will be determined based on project budget and duration. The budget must be within the spending limit; therefore, the optimal number of vessels, transport barges and tugs is determined based on appropriate estimates of the desired project outcomes. The cost of equipment like cutting tools has been included in the overall vessel costs. The time it takes to complete removal activities is primarily dependent on the number of resources allocated, especially removal and transportation vessels.

The cable removal is assumed to include only the inter-array cables, because the export cables are cut and buried at the terminating points. The length and weight of array cables for removal and transport depend on the size of wind farm, type of seabed, type of removal vessel, etc. The cables that lie on the seabed surface must be removed in a way so as to avoid concerns for other users of the sea. Most of this information is obtained from the survey done during preparation phase and the installation data available in wind farm databases. The vessels used for cable removal include the OSV and a cable-laying vessel, which cost respectively £2071.51 and £85,600 per day. The time required to complete the removal operation depends on the type of vessels used. A larger capacity vessel can remove more length from cables in a shorter time. Export cables are commonly not removed completely. However, if they are to be removed, a large vessel (cable removal vessel) will be required to lift the burial rocks or structures used to keep the cables in place.

The substation removal involves removing the topsides and foundation. A heavy lift vessel is used to remove the topsides and foundation of the offshore substation, whereas a smaller vessel such as an OSV is used for the removal of met towers. Barges and tugboats will be used to transport the removed items to shore for processing. The decommissioning cost of offshore substation and met mast depends on the number of offshore substations and met masts to be removed, type of vessels used and the assumptions made during estimations based on the weight of the structures. In the baseline wind farm, it is assumed that one offshore substation and six met masts (with jacket foundations) are removed. It is also assumed that the offshore substation and met mast removal will take 4.5 days and 2 days, respectively.

### 5.3 Logistics and waste management cost

The logistics cost includes the cost of personnel accommodation, port rental cost per annum (converted to daily rate) and onshore personnel costs. The cost of vessels and personnel costs for decommissioning activities are not accounted to avoid double counting. Ideally, all vessel day rates and mobilisation/demobilisation costs and personnel costs will be accounted for in this cost group; however, most available data provide decommissioning activity costs inclusive of the associated vessel costs. The accommodation and onshore personnel costs are £4500 and £150 per day, respectively. The port rental cost per annum is £13.4 million and the duration of the decommissioning execution is estimated to be 543.4 days. Thus, the port rental cost during the decommissioning project will be £19.9 million. Mobilisation costs for the JU and HLV are £138,000 and £276,000, respectively.

The waste management cost is made up of the cost of processing each component and onshore transportation from port to processing facility/landfill. These costs are dependent on the weight of materials to be transported and processed, the capacity of trucks and the cost of processing each item. The recyclable items are processed differently than non-recyclable items. The estimated salvage value of the recycled items is deducted from the waste management cost. The distance from the port to processing facility and landfill/scrapyard is assumed to be equal in this study. Table 4 provides the input data used to estimate the waste management cost. Recyclable and non-recyclable wastes are assumed to account for 60% and 40% of the total weight, respectively.

### 5.4 Post-decommissioning cost

The post-decommissioning cost is dependent on the cost of surveying a pre-set radius of the wind farm area, site clearance using different methods to ensure no dropped objects or other components from the installation phase remain on the seabed, cost of site monitoring (in the case where some assets such as export cables are left in place), site remediation and other miscellaneous expenses. The model used in estimating the total cost of post-decommissioning for this case is based on the summation of all the primary cost elements.

## 6 Results and discussion

In this section, the cost estimate results from each of the cost groups are presented and the findings are discussed. The cost contribution of different decommissioning phases and activities in total decommissioning cost is calculated and presented in Table 5. The total decommissioning cost was estimated by adding cost estimates of different decommissioning phases and activities.

As can be seen from Table 5, the decommissioning base cost estimate for the offshore wind farm ranges between about £132.8 and £229 million, excluding contingency costs. The total decommissioning cost estimate including contingency cost ranges between about £145.3 and £241.5 million. Figure 4 represents the contribution of different activities in low-range cost estimate of the offshore wind farm decommissioning project. As shown, the top three contributors are as follows: the wind turbine and foundation removal cost, planning and regulatory approval cost and the logistics cost, making up 62%, 18% and 17% of the total decommissioning cost, respectively. Waste management activities are estimated to generate a profit of £5.39 million. The salvage value of the components (e.g. steel) is estimated with the assumption that 60% of the total removed structural weight is recyclable (Shafiee et al. 2016).

**Table 3** Waste management methods for different wind turbine components

| Component | Waste management method |
|---|---|
| Wind turbine foundation | Recycle |
| Wind turbine tower and transition piece | Recycle |
| Blades | Energy recovery (incineration), landfill |
| Hub | Reuse, recycle |
| Nacelle | Reuse, recycle, incineration, landfill |
| Scour protection | Recycling, landfill, leave-in-place |
| Power cables (inter-array and export) | Recycle |
| Substation topsides | Reuse, recycle |
| Substation foundation/jacket | Recycle |
| Rocks | Leave-in-place |
| Platforms and ladders | Recycle |
| cables | Recycle |
| Miscellaneous, e.g. concrete mattress, rubber, plastics and PVC | Recycle, incineration, landfill, reuse in construction |
| Oils | Chemical waste treatment (refined and upcycled) |
| Marine growth | Use as sludge |

### 6.1 Planning and regulatory approval cost

The planning and regulatory approval cost is estimated to be about £23.4 million. This phase is the second largest contributor to the total decommissioning cost as it is composed of all the overhead costs within the decommissioning process, including the project management cost and environmental impact assessment survey cost. An approach to reduce this cost is to negotiate about the most appropriate contracts with suppliers and contractors, and wherever possible, in-house expertise can be capitalised on. Also, with increased contractor/operator experience, there will be potential cost savings; some research account for this as learning improvement cost savings, but it is excluded in the above estimate. The regulatory compliance cost is usually higher in countries where regulatory fees are required for approval and amendments. Overall, it depends on the wind farm size and regional government policies.

**Table 4** Data inputs for estimating waste management cost

| | | |
|---|---|---|
| $C_{\text{proc-WT}}$ | 92.04 | £/tonne |
| $C_{\text{proc-found}}$ | 46.02 | £/tonne |
| $C_{\text{proc-mettower}}$ | 46.02 | £/tonne |
| $C_{\text{proc-arraycable}}$ | 9102 | £/km |
| $L_{\text{array-cable}}$ | 133.11 | km |
| $W_{\text{wt}}$ | 55,250 | Tonnes |
| $W_{\text{found}}$ | 76,000 | Tonnes |
| $W_{\text{met tower}}$ | 570 | Tonnes |
| $T_{\text{ruck capacity}}$ | 24 | Tonnes |
| $C_{\text{truck}}$ | 0.41 | £/km |
| Distance to Landfill and Scrapyard | 50 | km |
| $C_{\text{landfill}}$ | 19.77 | £/tonne |
| $C_{\text{scrap}}$ | 205.4 | £/tonne |

Contingency planning must be well accounted for in order to lower the impacts of unforeseen events on the project cost. The potential risks must be identified and quantified in the cost estimates for the decommissioning project. The less the uncertainty within a decommissioning project, the less the planning and regulatory approval costs. Development of the most optimal contingency plan is a challenge, and the contingency allowance percentage is dependent on different factors such as the type of the asset to be removed, distance from shore and potential breakdowns. For example, a concrete gravity-based structure removal may pose more risk than a monopile foundation. The different factors must be taken into account to make sure that the risks are managed properly. In our case study, the main cost drivers identified in this phase include the project management and contingency. Until more data can be collected from different regions about offshore wind farm decommissioning activities, it will be difficult to estimate the range of planning and regulatory approval cost with lesser uncertainty.

### 6.2 Execution cost

From the results, it is confirmed that the execution phase is the costliest phase primarily because of the logistical provisions

**Table 5** The cost estimates for different decommissioning phases and activities

| Decommissioning phase | Decommissioning activity | Cost (£) |
|---|---|---|
| Planning and regulatory approval | | 23,401,965.98 |
| Execution | Wind turbine and foundation removal | 81,716,407.55 (min) 157,308,911.55 (max) |
| | Array cable removal | 1,573,004.80 (min) 22,162,777.58 (max) |
| | Substation and met tower removal | 1,642,313.99 |
| Logistics and waste management | Logistics | 22,578,722.03 |
| | Waste management | (5,386,510.65) |
| Post-decommissioning | | 7,274,512.94 |
| Decommissioning base cost estimate | | 132,800,416.63 (min) 228,982,693.41 (max) |
| Total decommissioning cost estimate (including 10% contingency) | | 145,313,411.69 (min) 241,495,688.48 (max) |

required for offshore marine operations. The execution phase makes up 64% of the total decommissioning cost. The wind turbine and foundation removal costs are the highest contributors to overall execution cost. The most influencing factors in this regard are the vessel requirements and the duration of the activities. Both are variable parameters which depend on the removal and transportation strategy adopted for each subtask. For example, cable decommissioning may be carried out by removal using reverse-installation (reel back unto the vessel), removal and cutting in sections or by burying the cable ends and leaving it in place. The types of vessel contracts must be selected according to the wind farm size and project constraints.

Among all execution subtasks, the wind turbine removal has the longest duration. Although the estimations of removal duration are currently based on estimations from the installation times and weather factors, because offshore wind farms are projected to move into deeper waters, decommissioning project duration for future offshore wind farms is not projected to scale linearly. Thus, further work can be done to collate data for decommissioning activities in deeper waters. Some suggestions for the key information that need to be collated methodically for offshore wind farm decommissioning projects are highlighted below:

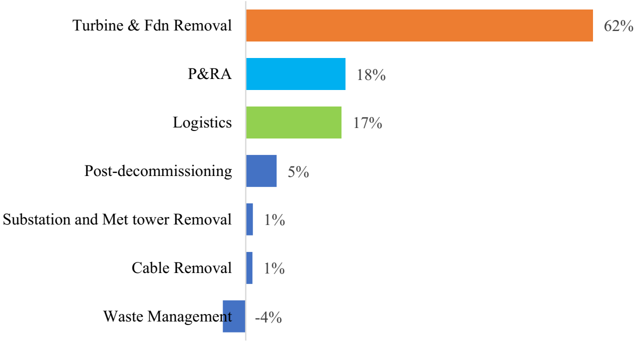


**Fig. 4** The contribution of different activities in low-range cost estimate of the decommissioning project

### 6.2.1 Duration of decommissioning activities

The duration to complete decommissioning activities is one of the most influencing factors in execution cost. There is likely to be a correlation between the duration of removal activities, the size/capacity of wind farm and the type of foundation. A reduction in task execution time, even for a few minutes, will accumulate into notable cost saving in decommissioning projects.

### 6.2.2 Number and size/weight of wind turbines

The number and size/weight of wind turbines influence the duration of cutting, lifting and transportation operations. The weight of wind turbines influences also the capacity of vessels to use for transporting the materials recovered from the site. In this study, the wind turbines with a total weight of 55,250 t took approximately 543.44 days to be removed. Based on the number and weight of the removed components, the deck space required can be directly estimated for different arrangements.

### 6.2.3 Water depth and distance to shore

The water depth and distance to shore can have a significant impact on offshore wind farm decommissioning costs. These factors influence the type of foundation structure and the length of transmission cables. In this study, the water depth of 30 to 45 m, distance to shore of 10 km, jacket foundation structure and cable length of approximately 133 km were

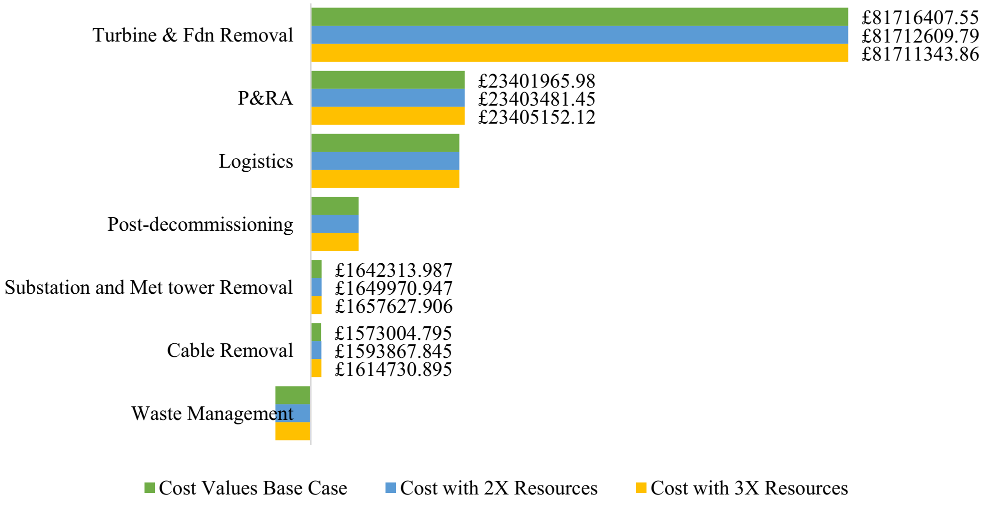


**Fig. 5** The effect of an increase in number of transportation vessels on the total decommissioning cost

taken into consideration. However, future decommissioning data can be obtained to determine how the different factors are correlated with total removal duration.

## 6.3 Logistics and waste management

Logistics cost contributes significantly to the total decommissioning cost—making up 17% of the total costs—excluding the costs included in the execution phase. Logistics is the third most critical cost driver in offshore wind farm decommissioning projects as it has a major impact on lifting, removal and transportation costs. The key cost drivers in this phase are the vessel requirements, activity durations and the number (size/weight) of wind turbines. With accommodation, onshore personnel and port rental costs at £4500, £150/day and £13.37 million per annum, the mobilisation and demobilisation cost will be £138,000 for jack up vessels and £276,000 for heavy lift vessels. The port rental cost has the highest potential for cost reduction. Port rental costs are dependent on the location and capacity of processing facilities. In our case study, the logistics cost is estimated to be £22.6 million. Waste management can be optimised by improving the recycling percentage. Opportunities for reuse or recycling can be explored for other industries outside the maritime industry. The cost of waste management is a negative cost of £5.39 million, showing profit. The cost is made of the cost of waste processing, transportation and landfill, which are £9.8 million, £464,000 and £1.07 million less the scrap value of £16.75 million.

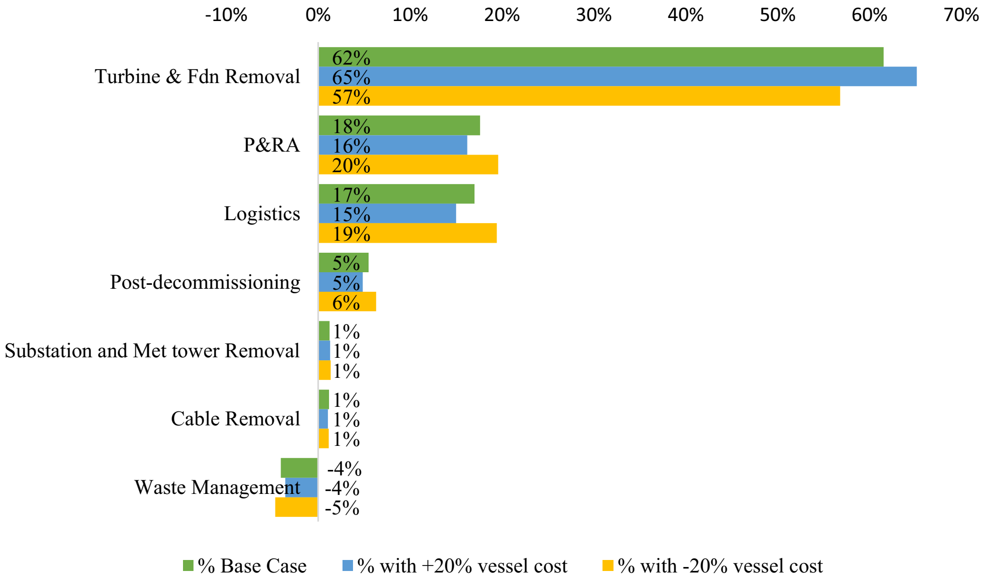


**Fig. 6** The effect of an increase (a decrease) in vessel rental charges on the total decommissioning cost

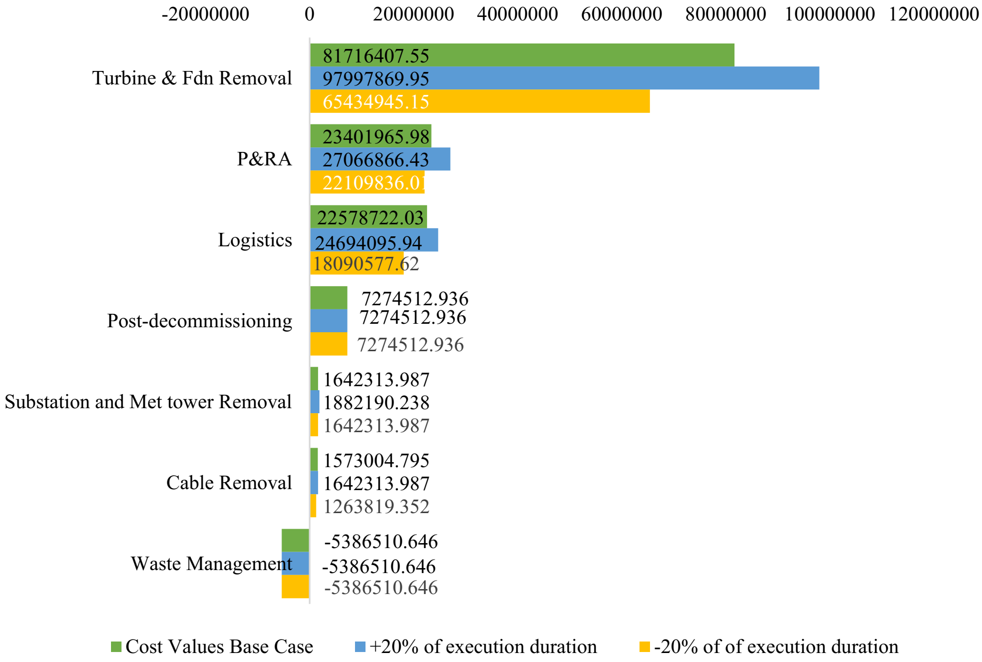


**Fig. 7** Effect of the duration of decommissioning activities on total decommissioning cost

## 6.4 Post-decommissioning

Post-decommissioning cost includes the survey, site clearance, site monitoring, site remediation and miscellaneous costs. The cost of site clearance is the largest contributor to this activity group. Site surveys will be done using ROVs at cost of £36,750. The cost of remediation was excluded in this study under the assumption that any seabed upheaval will settle with time. The site clearance cost is obtained by multiplying the cost of site clearance per area (£51,542/km$^2$) and the wind farm area (70.14 km). Site monitoring cost was obtained from Shafiee et al. (2016), which is £3.6 million per annum. This cost may vary from a case to another depending on the items left in place at the wind farm site. Miscellaneous costs are assumed to be £7500. The total post-decommissioning cost is estimated as £7.27 million.

## 6.5 Sensitivity analysis

In this section, we investigate the effect of abovementioned parameters on the total offshore wind farm decommissioning cost. Therefore, a sensitivity analysis is performed by

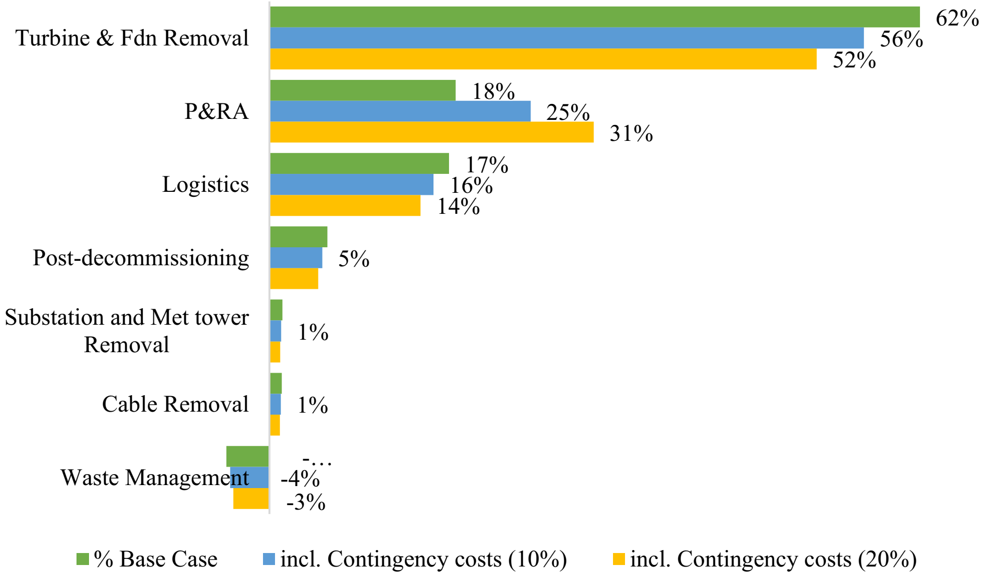


**Fig. 8** Effect of the contingency allocations on total decommissioning cost

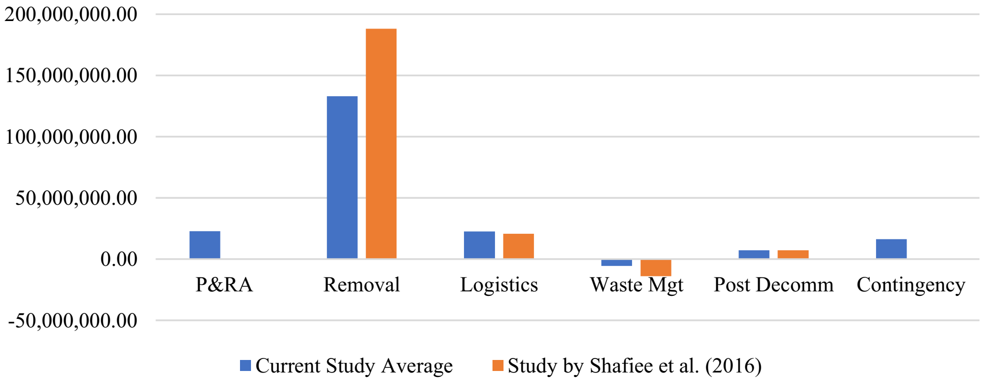


**Fig. 9** A comparison between the decommissioning cost estimates in this study and Shafiee et al. (2016)

changing four parameters, including the following: number of resources, vessel rental costs, activity durations and contingency provisions.

### 6.5.1 Changing the number of resources

In order to show how an increase in the number of resources will affect the total decommissioning cost, a sensitivity analysis is performed. The resources considered in this analysis include the number of removal vessels, transportation vessels, personnel and equipment (such as cranes). An increase in the number of removal vessels is observed to increase the decommissioning cost but reduce the duration of activities. The number of manpower required is different from an activity to another depending on the nature of skills required for each activity. The analysis shows that an increase in personnel has a notable impact on the overall decommissioning cost. Personnel cost for decommissioning activities can rise in two ways: an increase in the number of personnel per activity and an increase in the cost per offshore/onshore personnel. The impact of increased personnel cost on total decommissioning cost was investigated by increasing the number of personnel for each activity. When the number of personnel increases by 50%, the total decommissioning cost increases by 0.42% (equivalent to £667,000). Increasing the cost per personnel by 20% and 30% resulted in an increase in total decommissioning cost by 0.18% and 0.27% (equivalent to £287,630 and £431,446), respectively. Thirdly, depending on the equipment required (e.g. heavy cranes, cutting equipment, ROVs and generators), an increase in equipment costs can have a significant impact on the total decommissioning cost. To estimate the impact of increased equipment cost, an analysis based on the mobilisation/demobilisation cost of a heavy crane is carried out. If the cost increases by 20% and 30%, the total decommissioning cost will increase by 0.03% and 0.05% (equivalent to £55,200 and £82,800), respectively. The transportation vessels used for decommissioning include a tug and a barge. It is observed that when the number of vessels increases to two tugs and two barges, the cost of planning and regulatory approval and removal activities will increase significantly. Figure 5 shows the effect of an increase in the number of transportation vessels on the total decommissioning cost. As can be seen, doubling the number of transportation vessels increases the total decommissioning cost by 0.02%, while tripling the number of transportation vessels increases the costs by 0.04%. However, the additional cost due to an increase in the number of transportation vessels is less than the overall cost saving based on its positive impact on reduced project duration. Therefore, it is concluded that hiring more than one transportation vessel will be beneficial to the project.

### 6.5.2 Changing the vessel rental charges

The effect of a 20% increase and decrease in removal vessel rental charges on the total decommissioning cost is analysed and the results are shown in Fig. 6. As can be seen, when the removal vessel rental charges increase by 20%, the wind turbines and foundation removal cost increase by 3%. This increases the total decommissioning cost by £17.6 million. This is a significant increase, although the estimate is conservative in nature. Future market trends are uncertain and difficult to predict and depend on the value of money at the time of decommissioning. Therefore, inflation must be managed adequately by exploring potential hedging mechanisms.

### 6.5.3 Changing the duration of decommissioning activities

The regulators oblige the wind farm owners to complete the decommissioning of their assets within a standard time frame. The duration of an offshore wind farm decommissioning project will critically impact its total cost. The impact of a 20%

increase and decrease in duration of activities on the total decommissioning cost is analysed, and the results are shown in Fig. 7. It is observed that if the duration of activities decreases by 20%, the total decommissioning cost will decrease between 17 and 18% (equivalent to £22.3 to £41.6 million). Some factors are identified to have the largest impact on the decommissioning duration. These include the following: removal and transportation time (including mobilisation and demobilisation time), removal method, cable burial/removal rate and the transportation strategy.

#### 6.5.4 Changing the contingency allocation

Offshore wind farm decommissioning activities are susceptible to uncertainties related to schedule, finance, weather and other potential unforeseen circumstances. Hence, it is important to evaluate the cost implication of increased contingency. The risks of a project have to be reduced to as low as reasonably practicable (ALARP) and provisions must be made to account for risks. Contingency allocation serves as a potential avenue for decommissioning cost reduction, especially if risks can be adequately identified, quantified and mitigated. In order to evaluate the effect of contingency allowances on the total decommissioning cost, different contingency percentages are considered. The total decommissioning cost is estimated for two cases of 10% and 20% contingency allocations and the results are shown in Fig. 8. If a lower risk is expected, 10% is allocated as the benchmark contingency cost. However, if higher risks are expected, the contingency of 20% will be allocated.

As can be seen, a 10% increase in contingency allocation increases the offshore wind farm decommissioning cost by £12.5 million.

### 6.6 Validation of the results

In order to validate the decommissioning cost estimates for the baseline offshore wind farm, the results of this study are compared with those reported in Shafiee et al. (2016). The results of the comparison are shown in Fig. 9. The average decommissioning cost in this study was estimated as £196.7 million, compared with £202.4 million as estimated in Shafiee et al. (2016). The decommissioning cost estimates are not exactly the same because not all cost elements were accounted for in Shafiee et al. (2016). This study takes into account the cost associated with planning and regulatory approval, and contingency allocations. Classifying the cost elements in appropriate groups will help asset managers better monitor the cost critical components. If the planning and regulatory cost is included in the removal costs, it will be more challenging for factors such as process optimisation to be factored into potential cost reduction avenues.

## 7 Conclusion and future outlooks

The wind energy industry will experience an increasing number of wind turbine decommissioning activities in the coming years. Therefore, it is crucial for wind farm owners/operators to identify high-cost areas and establish some opportunities and priorities for cost savings. The lifecycle costing (LCC) has been applied as an effective method to assess the total cost of wind energy development, with taking into consideration all expenditures over the entire life cycle from the initial investment costs to subsequent maintenance and operating costs through to salvage and resale value. This paper performed an LCC analysis for offshore wind farm decommissioning projects using a cost breakdown structure (CBS) approach. Our analysis enables wind farm owners/operators to identify the most critical cost factors and evaluate the effects of any improvements on the total decommissioning cost. The decommissioning activities for offshore wind farms were divided into four key phases, including the following: planning and regulatory approval, execution, logistics and waste management and post-decommissioning. Some mathematical models were proposed to estimate the costs associated with different activities involved in decommissioning of a 500 MW baseline offshore wind farm. Finally, the total decommissioning cost including contingency cost provisions was calculated.

The key findings from the decommissioning cost estimation were that the removal of wind turbines and foundation, logistics and planning and regulatory approval activities accounted for the largest proportion of the total cost. The key cost drivers included the vessel rental charges, duration of activities, contingency cost allocations and potential market changes. These cost drivers should be the primary focus for the wind energy industry to reduce decommissioning costs for future deepwater wind farms. A sensitivity analysis was also performed to evaluate the effect of any changes in different parameters on the total decommissioning cost.

Future areas of research include optimisation processes that can help to reduce the duration of decommissioning activities, improve the efficiency of transportation vessel schedule, mitigate the contingency/financial risks and improve the materials recycling methods to increase income from waste management. Improvements in logistics, contingency planning and removal methods are possible avenues of research in the future, with the aim of making the decommissioning process a more sustainable part of the renewable energy systems lifecycle.

# Appendix

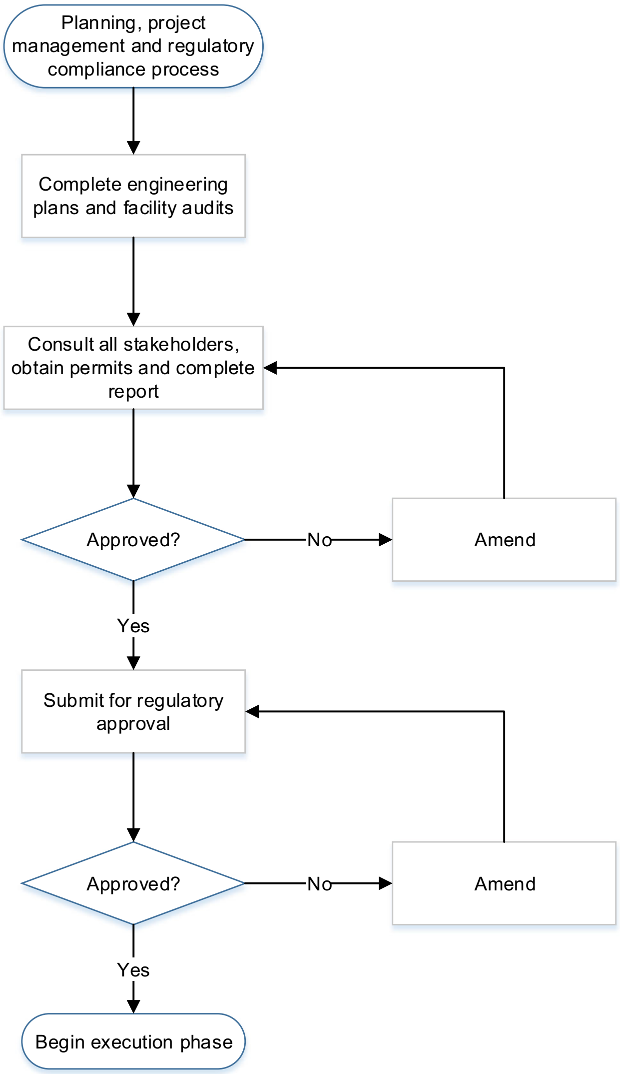


**Fig. 10** A flowchart for planning and regulatory approval of offshore wind farm decommissioning projects

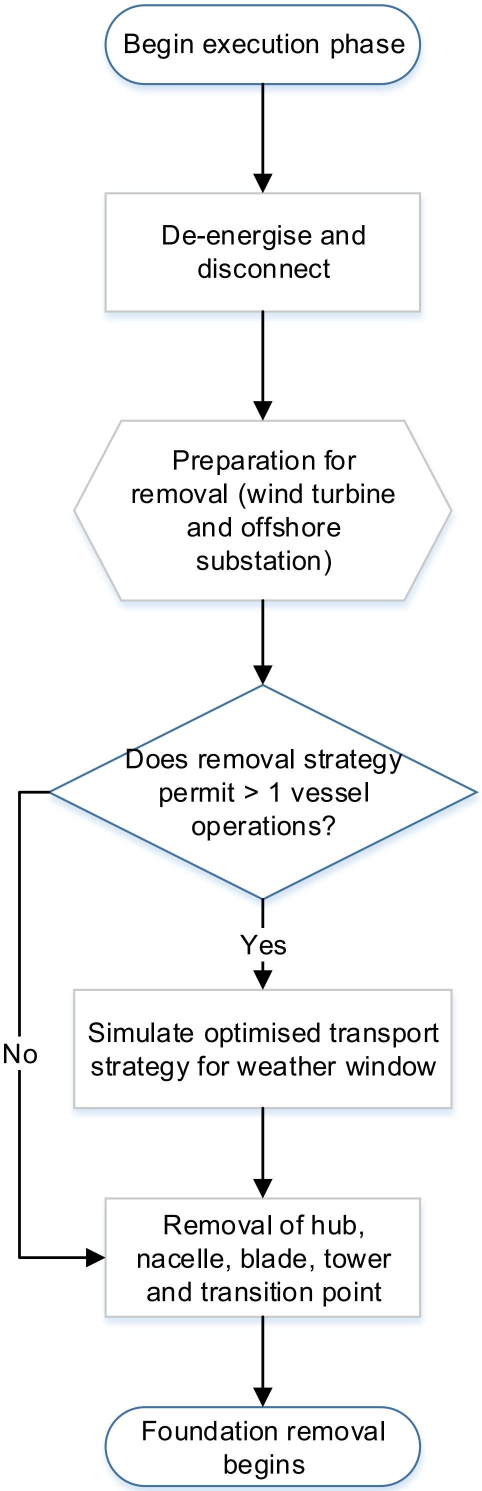
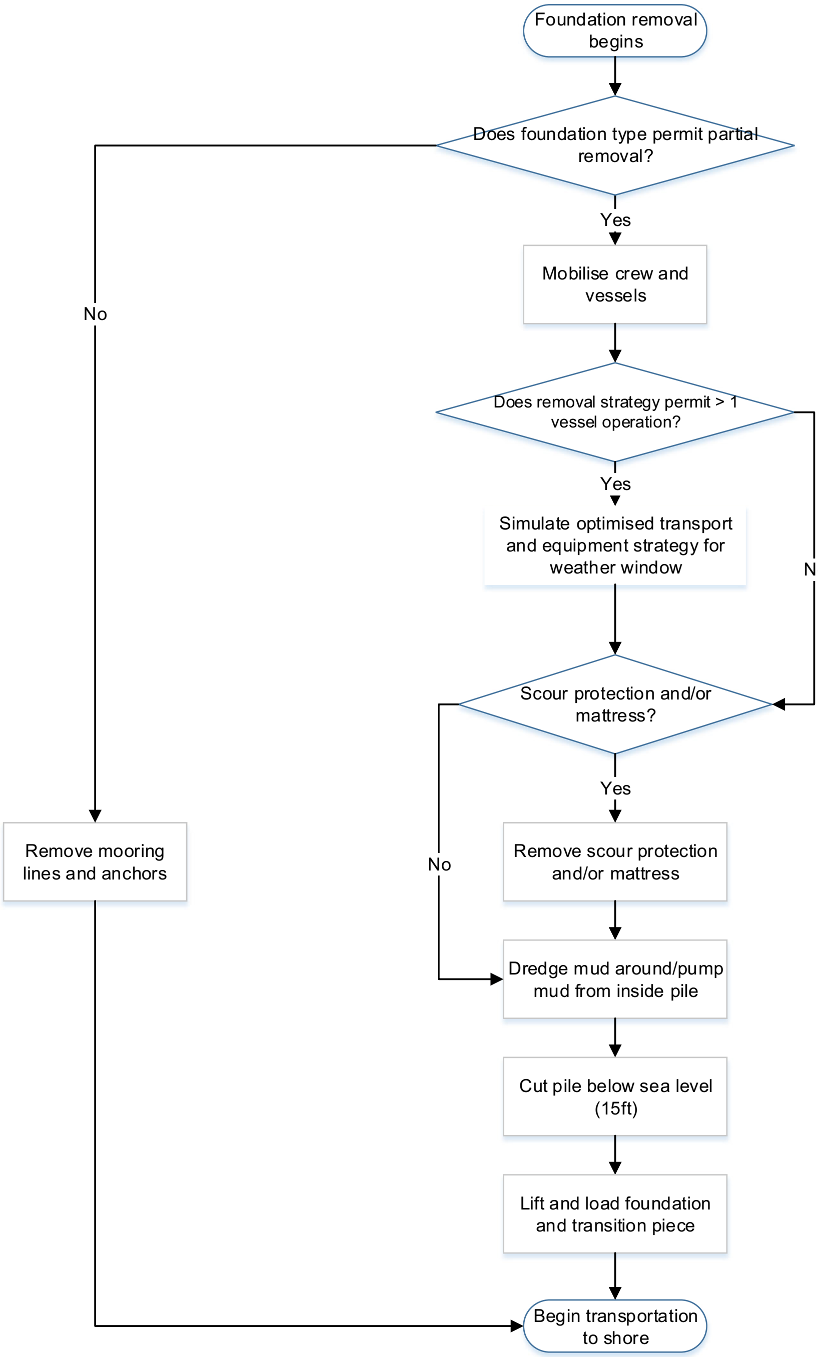


**Fig. 11** A flowchart for the execution phase of offshore wind farm decommissioning projects

**Fig. 12** A flowchart for the foundation removal activity in offshore wind farm decommissioning projects



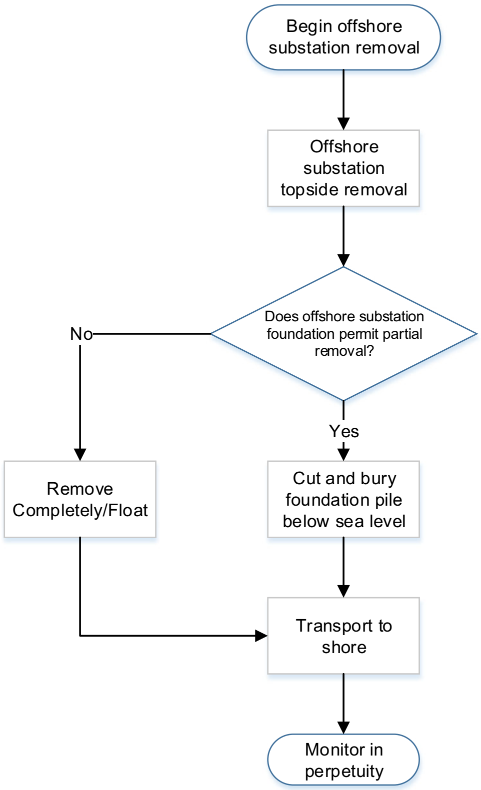


**Fig. 13** A flowchart for substation removal activity in offshore wind farm decommissioning projects

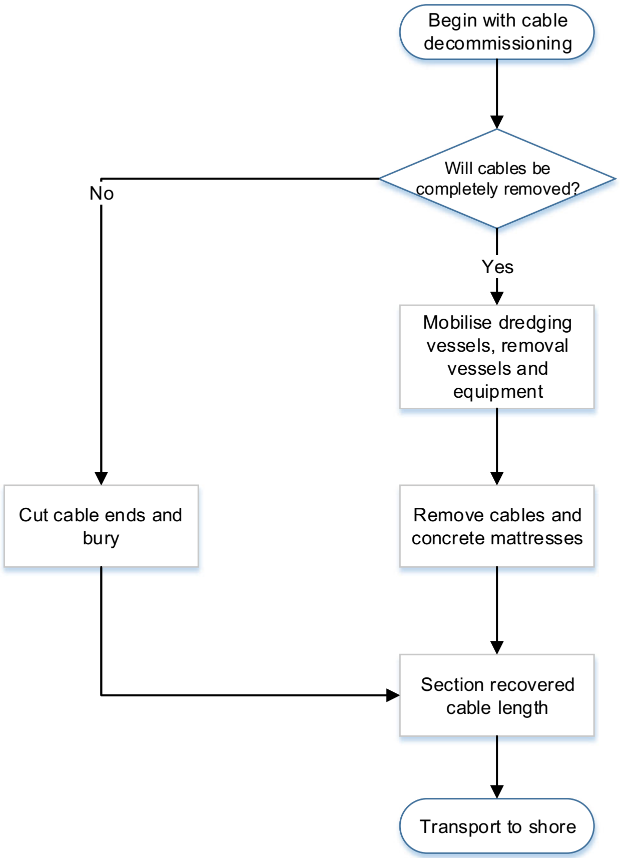


**Fig. 14** A flowchart for cable decommissioning in offshore wind farms

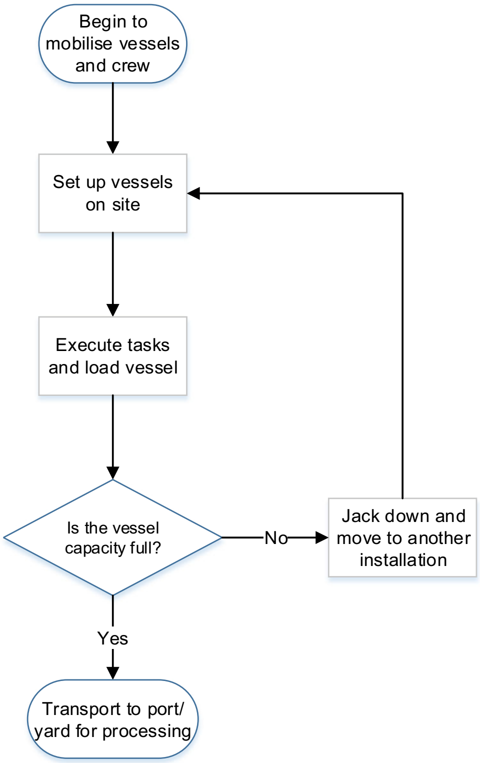


**Fig. 15** A flowchart for logistics planning in offshore wind farm decommissioning projects

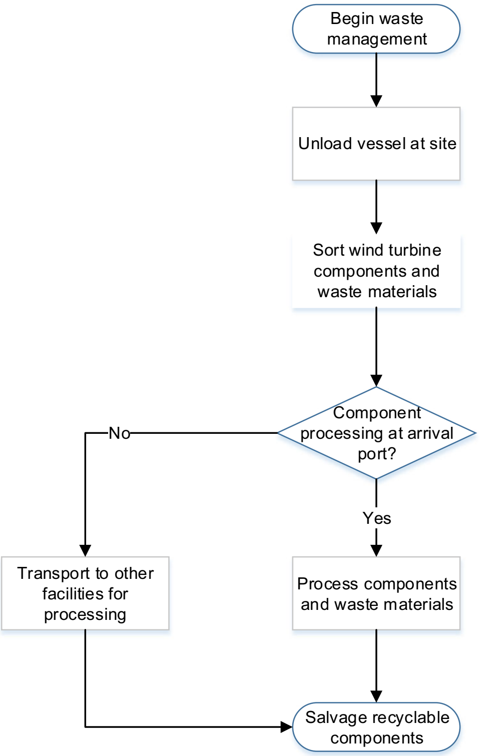


**Fig. 16** A flowchart for waste management in offshore wind farm decommissioning projects

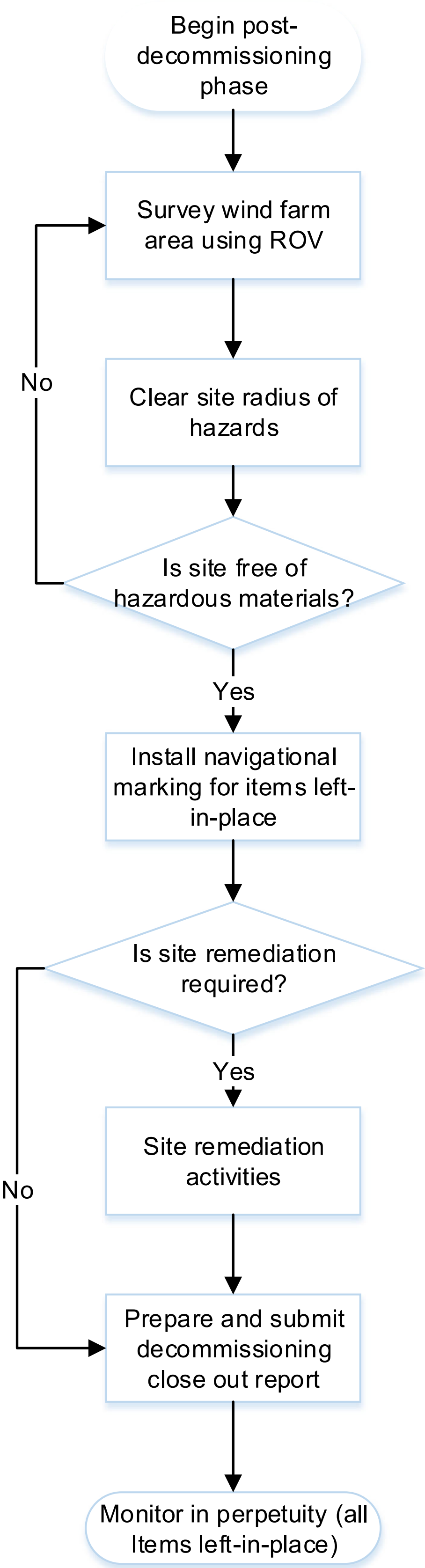


**Fig. 17** A flowchart for the post-decommissioning process in offshore wind farms

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