Finishing well: sustainability approach for offshore wind farm decommissioning

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ABSTRACT

For offshore wind farm decommissioning, many factors must be taken into consideration. So far, only few experiences from the decommissioning of smaller-scale windfarms that were close to shore, have been made. Hence, there is still uncertainty about e.g. foundation structure dismantling, their time and costs estimation, technical feasibility of removal techniques and the environmental impact as well as safety and acceptance aspects. In the *SeeOff* R&D project "Development of efficient strategies for offshore windfarm decommissioning", we are developing a process-oriented and indicator-based approach for analysing decommissioning strategies with a more holistic assessment. Economic, environmental and social aspects are considered in order to identify sustainable decommissioning strategies for offshore wind farms.
The approach is to be applied to a reference wind farm which is considered to be a representative wind farm due to the most common foundation type and turbine model in the German Exclusive Economic Zone.
A further aim is to publish a handbook which can be used as a guide and basis for finding sustainable strategies for the specific project.

1. INTRODUCTION

Offshore wind farms as a renewable energy should be sustainable over the entire lifecycle of a wind farm and its components. Several countries have declared the long-term goal to reach a climate-neutral economy by 2050 in line with the Paris Agreement and have placed it into law such as e.g. Denmark, France, Germany, Hungary, the UK and New Zealand. This goal can only be reached by an energy economy based on renewable energy. To date, a number of life cycle assessments of either offshore wind turbines or whole wind farms have been carried out (Wagner et al. 2011; Frischknecht et al. 2004; Bounou 2016), quantifying the environmental impact and considering the lifecycle up to the dismantling and return transports of the component or material used. However, these and a recently published study (Jensen 2020) show, that there is a need for considering circular economy in decommissioning of offshore wind farms, indicating that there are factors being disregarded for the end of life (EoL) of offshore wind farms until now. Moreover, the approval of the construction of a wind farm goes along with an environmental assessment and monitoring which continues during and after the construction phase in several countries like the UK, Germany or Denmark. Costs are carefully planned for the installation phase as well as studies undertaken for the public acceptance of proposals, installation or operation of a wind farm (e.g. Sonnberger & Ruddat 2017, Walker et al. 2014, Ladenburg & Möller 2011), but little of it seems to be done for the decommissioning of a wind farm. Another study confirms that little attention has been given to the decommissioning phase till that date (Topham & McMillan 2017). Most frequently, for those decommissioning concepts that have been opened for public access, a not very detailed method for the decommissioning offshore is given (Jensen 2020). In Germany for example, the decommissioning concepts are being submitted as a prerequirement and as a basis for the calculation of the provisions and securities to be proven to the federal authority in order to obtain the construction approval. As such it neither contains the assessment of the environmental impact nor considers social factors but is only economically motivated. Within the minimum standard for construction it is stated that "in good time prior to the end of the operating phase" (BSH 2015) a detailed decommissioning plan must be submitted. There is no further specification apart from the detailed technical procedure and waste disposal verifications so far. However, the Standard Investigation of the Impacts of Offshore Wind Turbines on the Marine Environment (StUK4) suggests that different dismantling techniques will have different environmental impacts for which a standardised monitoring scope will be established at a later point in time (BSH 2013). So far there are no established sustainability indicators within the offshore wind decommissioning industry. Although attempts have been made to find such (Evans et al. 2008, Smyth et al. 2015, Topham & McMillan 2017), some scientists call for a holistic approach for decision support. Hence the research project "SeeOff - Development of efficient strategies for offshore wind farm decommissioning", which is funded by the Federal Ministry for Economic Affairs and Energy in Germany, aims at using a structured approach in order to evaluate different decommissioning scenarios and developing efficient decomissioning strategies. In the following, the development of indicators will be described as well as the path to different decomissioning scenarios with an outlook onto the holistic assessment.

2. APPROACHING DECOMMISSIONING WITH SUSTAINABILITY ASPECTS

In order to make offshore wind energy sustainable over the entire lifecycle, a sustainable approach needs to be considered in strategic decision making processes, including the End of Life Strategies. In 2015, the United Nations published the Agenda 2030 with a total of 17 Sustainable Development Goals (SDG) for the economic, environmental and societal sectors (UN 2015), representing the three pillars of sustainability. These were used as the main categories in the SeeOff project to find key objectives to be achieved and measured with suitable indicators derived from the SDGs. The key aspects within those categories, together with its objectives and indicators were determined and discussed in a designated workshop with a wide range of stakeholders such as government authorities e.g. Federal Maritime and Hydrographic Agency, industry partners, including wind farm operators and service companies as well as other organisations associated with the offshore wind or decommissioning industry. An overview of the results is given in Figure 1, showing each sustainability category with its aspects, objectives and indicators.

2.1 CATEGORY OBJECTIVES

The main objective as described above is a sustainable decommissioning design, i.e. cost-effective, environmentally friendly, safe and socially accepted. Following, the objectives for each category (see Figure 1) shall be described.
Considering the category of economy the objective is to decommission economically efficient. This means that the decommissioning of the existing systems should be carried out at the lowest possible cost from a business perspective. Efficiency describes "the ratio of value-based output to value-based input". The economic efficiency hereby evaluates the use of resources with the associated costs.
Regarding the category environment, three objectives have been derived to be of possible importance. Those are (1) the minimization of greenhouse gas emissions as a global objective and strive to combat climate change and (2) the protection of biodiversity as an objective that is both internationally important (e.g. in the UN Convention on Biological Diversity (UN 1992) or Marine Strategy Framework Directive 2008/56/EC) as well as in national law (e.g. BNatSchG), (3) the aim for high resource efficiency as guiding principle of circluar economy and which has been set as a goal by the EU within the Circular Economy Action Plan in 2019 (EU 2020). Looking at the social category, the safety of those working within the offshore wind industry is, of course, a major objective. Several international and national laws and standards guide the work offshore and organizations such as the Global Offshore Wind Health and Safety Organization (G+) have formed with the aim to reduce health risks and

increase safety within the offshore wind and ship transport industry. Within Germany, under the "Common German Occupational Health and Safety Strategy" since 2007, national occupational health and safety goals are formulated, among which was the reduction of severity and frequency of accidents at work within the program "construction and assembly work". This goal has been chosen as an objective for the decommissioning of offshore wind and as such, hazards should be minimized. Finally, concerning the measurement of the acceptance within the society, it can be stated that the public's support for the expansion of renewable energies and wind energy is extremely high. Surveys commissioned by the Agency for Renewable Energies and the specialist agency for wind energy show that both general agreement for renewable energy (89 %) and that of wind energy use (82 %) are widespread (AEE 2016; Specialist Agency Wind Energy on Land 2019). Criticism is usually exercised on individual aspects (efficiency, costs, environmental influences, obstruction of view, etc.) and thus repeatedly puts the topic at the center of public discussions. As a result, the perceived acceptance is lower than the actual one. This partially has a (large) impact on political decision-makers. Hence, the decommissioning strategies should be analysed regarding their possible impact on public acceptance.

2.2 DETERMINATION OF INDICATORS

Following, the determination of the indicators as well as their calculation is described in brief. For measuring economic efficiency it was determined, that the present value of costs per MW decommissioned can be used for comparison. Because costs vary over time, a simulation is needed to consider the existing uncertainties and dependencies. Therefor it is important to identify the relevant factors of each process (i.e. duration, costs, variations). A stochastic Monte Carlo simulation is then carried out for each decommissioning strategy to calculate the average and spread of costs per MW decommissioned.

Sustainable decommissioning of offshore wind farms							
Category	**Economy**	**Environment**				**Health and safety**	**Acceptance**
Aspect	Economic efficiency	GHG-Emission	Biodiversity	Ecosystem services	Resource efficiency	Safety at work	General acceptance
Objective	Economic efficient	Low GHG-Emission	Minor local impact	Minor local impact	High resource efficiency	Few hazards	High public acceptance
Attribute	(Present) value of costs	CO2-Equivalent	Species richness	Secondary production	Recycling rate	Hazard level	Level of acceptance

Figure 1: Sustainability aspects, objectives and attributes for the three main categories of sustainability (health and safety and acceptance refer to the category social)

As a measurement for greenhouse gas emissions, the CO_2 equivalents are calculated by gathering data for the decommissioning processes. Here either emission data are used if available such as published CO_2 emission data from the European Thetis Database for shipping, Probas Database for truck transport from the German Environment Agency or data provided by companies within the i.e. logistic sector. If emission data are not available, they are estimated by the duration of the process, the fuel consumption range as well as the emission factor specific to the energy source.

In order to evaluate the possible local impact of the different decommissioning scenarios, the indicators of species richness and secondary production were discussed and found to be of interest for research. The determination of those indicators are limited to the offshore wind farm site.

To answer the question whether the resources and materials are managed in an efficient way, indicators on material as well as waste recycling and recovery rate (Reisinger et al. 2015) can be used. The indicator of recycling rate is proposed to be used on a national level within the frame of the Sustainable Development Goals. For offshore wind decommissioning, it is calculated for the material recovered from the offshore site and brought back onshore for material utilization versus the amount of waste from OWF decommissioning.

For assessing the safety at work, as per law, different risk assessments and safety studies are normally carried out and reach down to a very detailed level as a construction project is being planned and carried out. In Germany, a so called hazard assessment needs to be done for each work process. Within this research, this tool is being used to determine the hazard level of different decommissioning strategies with the focus on offshore activities as these are often related with risks and hazards beyond those encountered on land. The hazard assessments are based either on risk assessments of the companies involved or carried out in expert interviews.

A challenging estimation is the public acceptance of different decommissioning strategies. Here, an acceptance value is to be determined by carrying out a public survey.

The presented indicators are measured or estimated for the decommissioning processes of a reference offshore wind farm (see Table 1). This is characterized by a widely used wind turbine generator type, foundation and other infrastructure such as inter-array cables.

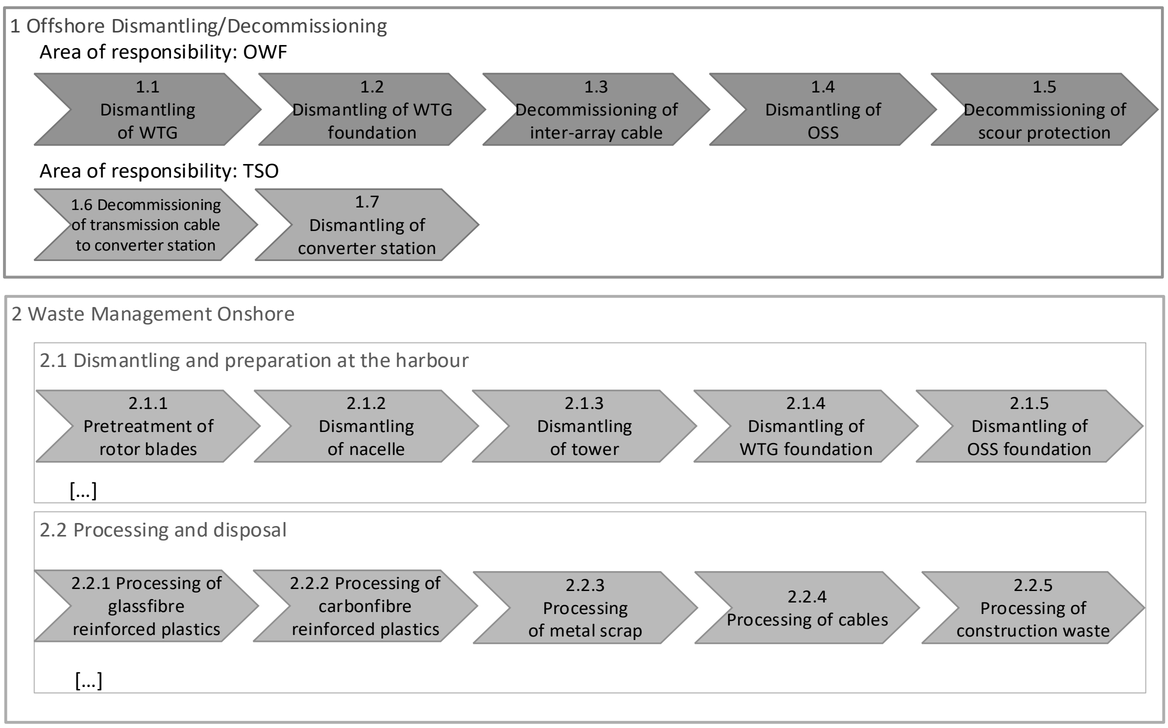

Figure 2: Process Overview (excerpt)

Table 1: Reference Offshore Windfarm and system boundaries

OWF	Reference OWF
WTG number and type	80x Siemens 3.6 120WT
WTG Foundation	Transition Piece (TP) with grouted connection to Monopile (MP)
Mean water depth	26,2±2,5m
Inter-Array Cable	33 kV
Scour protection	Yes
System boundary	Converter station

Following the build-up of decommissioning strategies is being explained in more detail.

3. DECOMMISSIONING STRATEGIES

By using a process-oriented approach to assess the decommissioning strategies regarding their sustainability, offshore and onshore processes and process options were modelled based on information given by executing companies, consultancies as well as literature. Figure 2: Process Overview (excerpt)Figure illustrates the processes included in this project. Only the operative processes of the dismantling work at sea up to the recovering of a secondary raw material are modelled. Hence preceding phases such as the decommissioning planning, tendering or approval process as well as possible other paths of re-use or refurbishment are not being considered within this frame. In order to develop decommissioning strategies for further assessment, the processes within i.e. "Offshore Dismantling", were first analysed regarding possible process options. These can be derived from:

(1) Variation of logistic setups and concepts (i.e. feeder concept vs. shuttle concept)
(2) Different extent of decommissioning (full removal vs. partial removal)
(3) Decommissioning technologies (high pressure abrasive water jet cutting, diamond wire saw cutting and vibratory extraction)
(4) Unloading options at harbour (Roll-off vs. lifting).

Afterwards, possible process options were selected based on a number of criteria, e.g:

(1) State of the art (minimum technology readiness level of 8)
(2) Data availability
(3) Hazard potential or
(4) Environmental relevance.

These selected process options were then combined to feasible decommissioning strategies in form of scenarios. A base scenario is included describing the path of "installation backward", using the same vessel and segmentation of components. Starting from this base scenario, single variations are being made regarding the option parameters given in Table 2. As a result, a total number of ten scenarios is going to be evaluated further. The most variations exist regarding the decommissioning technique of the wind turbine and its foundation as well as the logistic setup.

Table 2: Example of base scenario for process 1.2 – Dismantling of the wind turbine generator foundation

Option parameter	Base Scenario
Extent of decommissioning	Cut min. 1 m below seabed level
Dismantling steps	Cut below TP to separate from MP
Dismantling technology TP	High pressure abrasive water jet cutting from inside
Dismantling technology MP	High pressure abrasive water jet cutting from inside
Disassembly offshore	No further disassembly of any component offshore
Logistics	Jack-Up vessel
Unloading	Lifting with crane of Jack-Up vessel

However, three of the ten scenarios consider the partial removal by either leaving the scour protection, inter-array cables or a few meters of foundation above seabed in place.

In order to measure the processes with the described indicators under 2.2, they were modelled on an activity level using Business Process Modelling Notation (BPMN). Here, 'activity' is a generic term for the work or task performed. This is especially needed for the indicators of greenhouse gas emissions as well as the determination of the hazard level, where the hazards need to be assessed for each activity and hence with a higher level of detail. On the other hand, the analysis of the costs will be carried out at the process level based on a resource orientation at an activity level with the related variations as well as uncertainties.

4. OUTLOOK: HOLISTIC ASSESSMENT

From our perspective, the complexity of offshore wind farm decommissioning requires a holistic assessment, that is capable of incorporating various sustainability objectives and indicators. Several studies have suggested or applied Multi-criteria decision analysis (MCDA) for offshore wind farm decommissioning (Fowler & MacReadie 2015, Lozano-Minguez et al. 2011, Kerkvliet & Polatidis 2016). This refers to a set of methods to assist complex decision making. They provide structured frameworks to compare the performance of different scenarios and enables the consideration of all indicators. Another advantage of the MCDA is that it can handle a wide range of data types (Mendoza & Martins 2006) such as qualitative and quantitative data. Hence, the method of MCDA is going to be applied on the determined decommissioning scenarios. It is assumed that some scenarios will show a better performance regarding environment, while others may show a better economic or safety performance. The results of this analysis yet to be carried out, will be subject of future publications and further discussion.

5. CONCLUSION

The process-oriented and indicator-based approach with a holistic assessment of decommissioning scenarios outlined here, presents an established method to address high-complexity decisions such as the comparison of decommissioning scenarios and selection of efficient decommissioning strategies. The study so far has revealed a large set of possible variations within offshore wind farm decommissioning. However, the variation of the extent of decommissioning is subject to international and national regulations and technical feasability of decommissioning techniques is yet to be proven for some technologies. A variation within the logistic setup might become unreasonable from a cost perspective when it comes to a specific wind farm decommissioning but an evaluation might uncover e.g. positive environmental effects, such as an emission of less greenhouse gases. As offshore wind farm decommissioning is still in the beginning, the results of studies such as the *SeeOff* research project can contribute in making offshore wind energy sustainable by using a holistic approach to assess different decommissioning strategies, including offshore dismantling and onshore waste management processes. Although it is being applied to a reference offshore windfarm, it is aimed to be a method that can be transferred to other decommissioning projects within the offshore wind industry.

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