# Challenges of decommissioning offshore wind farms: Overview of the European experience

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**Abstract.** In the coming years, an important number of offshore wind turbines will reach the end of their initially planned service life. In a wind turbine end-of-life scenario, owners can decide between extending the life of the asset, repowering the site or decommissioning. This decision- making process is affected by important sources of uncertainty, especially in offshore environments. The limited experience makes the decommissioning procedure challenging, as it is still largely unexplored. This work assesses the current state of knowledge about the challenges surrounding the decommissioning process of an offshore wind farm. The four main challenges encountered are identified and analysed in detail, namely the regulatory framework, the overall planning of the process, the logistics and vessels' availability, and the environmental impacts confronted. Ultimately, this paper aims at stimulating the dialogue among stakeholders and raising the awareness of adequately regulating and preparing the upcoming decommissioning of offshore wind farms in Europe.
**Keywords:** Offshore wind, End-of-life strategies, Decommissioning, Challenges.

## 1. Introduction

Since the commissioning of the first offshore wind f arm i n 1 991, the offshore wind industry has successfully evolved, and a total installed capacity of 18.5 GW can be now found in Europe [1]. While the main problems previously encountered were related to the planning and construction [2], the new concerns emerge regarding the ageing of the fleet [3], which are shared with the onshore wind industry. Nevertheless, the required decisions in a wind turbine end-of-life scenario are more critical offshore, due to the natural difficulties and constraints posed by the environment.

Wind turbine end-of-life has recently emerged as a topic of major interest. Almost 30% of the total installed wind turbine capacity in Europe will be older than 15 years by 2020 [3]. Given the wind turbine service life is of 20 years, there is an urgent need to thoroughly prepare for the different end-of-life possible scenarios. By the end of this 20-year service life, wind farm operators need to decide between the extension of the asset lifetime, repowering or decommissioning the site [4]. The two first options may be explored under the right conditions, with respect to the technical, economic, regulatory and environmental aspects. Nevertheless, regardless the final service life of a wind turbine, decommissioning will always happen [5]. Despite the important challenges, this topic is still largely unexplored mainly due to the lack of experience [6].

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The present work assesses the current state of knowledge about the challenges surrounding the decommissioning process of an offshore wind farm. A thorough review of the current state-of-the-art has been conducted, based on the available scientific literature, together with the information documenting the few actual experiences of offshore wind farm decommissioning. As a result, four key challenges have been identified and studied in detail, i.e. the regulatory framework, the planning of the decommissioning procedures, the logistics and vessels' availability, and the environmental impacts involved. Ultimately, this paper aims at stimulating the dialogue among stakeholders and raising the awareness of adequately regulating and preparing the upcoming decommissioning of offshore wind farms in Europe.

The paper is organised as follows. Section 2 describes the research methodology combining literature review and media information documenting the existing experiences of already decommissioned projects in Europe. These experiences are described in detail in Section 3 together with background information on the offshore wind assets' life in Europe. Section 4 presents results of the challenges surrounding the decommissioning of offshore wind farms as an outcome of the review of scientific literature; the four identified challenges are discussed. Conclusions are presented in Section 5.

## 2. Methodology

As previously stated, the decommissioning of offshore wind farms is still a largely unexplored topic. Consequently, the available scientific contributions contain limited information on the current practice within the offshore wind industry. To overcome this shortcoming, further data was gathered through the documentation of the limited experience of already decommissioned wind farms, which only refer to Europe and are mainly available through press articles.

From the review of all the collected information, a critical analysis of the procedures involved in the decommissioning of offshore wind farms was performed. Additionally, the major aspects that condition the process were assessed together with their interaction. As a result, four main challenges have been identified and covered in detail. Further study of these should lead to the design of adequate decommissioning procedures, such as a guideline elaboration on recommended practices for an appropriate offshore wind farms dismantling.

## 3. The European experiences of offshore wind farm decommissioning

With a total installed capacity of 18.5 GW, Europe is the world's leader in the offshore wind industry [1]. Nevertheless, the development of wind energy in the offshore sector came later than in the onshore environment. As a result, the offshore wind fleet is still predominantly young. This situation will dramatically change in the coming years, as more and more offshore wind turbines will reach the end of their 20-year design life. The annual number of offshore wind turbines that will reach the end of their planned service life in Europe is illustrated in Figure 1. Between 2020 and 2030, decisions between lifetime extension, repowering or decommissioning will be needed for over 1,800 offshore wind turbines. From 2030 to 2040, almost 20,000 offshore wind turbines will be facing these end-of-life scenarios in Europe.

Although the importance of the required end-of-life decisions for offshore wind turbines might be seen as a future problem, Europe has already witnessed the end of the service life and decommissioning of several projects. A summary of the decommissioned offshore wind projects is presented in Table 1. For the two last listed projects, Blyth and Beatrice Demo, decommissioning has not yet ocurred although it has already been planned as their operation has ceased. Prototype projects, such as Nogersund (Sweden, 0.22MW), Windfloat (Portugal, 2MW) or Hooksiel (Germany, 5MW), have been discarded in this study.

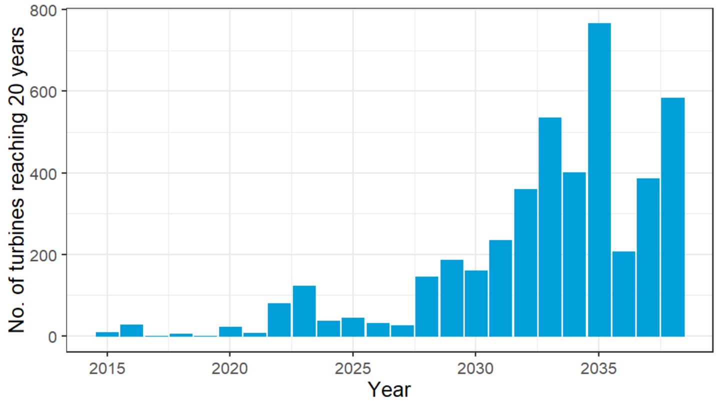


**Figure 1.** Number of offshore wind turbines reaching 20-years of operation annually in Europe. Source: [7].

**Table 1.** Offshore wind farms decommissioned to date. Source: [7].

| Wind farm | Country | Capacity and nb. of WTs (MW) | Foundation type | Years of operation | Decommissioning year |
|---|---|---|---|---|---|
| Yttre Stengrund | Sweden | 10 (5 x 2MW) | Monopiles | 15 (2001-2015) | 2015 |
| Lely | Netherlands | 2 (4 x 0.5MW) | Monopiles | 20 (1994-2014) | 2016 |
| Vindeby | Denmark | 4.95 (11 x 0.45MW) | Monopiles | 26 (1991-2017) | 2017 |
| Utgrunden I | Sweden | 10.5 (7 x 1.5MW) | Monopiles | 18 (2000-2018) | 2018 |
| Blyth | UK | 4 (2 x 2MW) | Monopiles | 13 (2000-2013) | 2019 |
| Beatrice Demo | UK | 10 (2 x 5MW) | Jacket | 8 (2007-2015) | 2024-2027 |

From Table 1 it can be noted that only two wind farms reached their initially planned service life: the projects Lely and Vindeby [8, 9]. In the case of Vindeby, the lifetime of the asset was even extended until 26 years of operation. For the rest of the cases, decommissioning occurred or is expected to happen before reaching the end of their planned service life. This highlights the high uncertainty related to the wind turbine end-of-life scenario for the offshore environment.

From a more generic point of view, The necessary activities to be performed are detailed in several contributions [5, 10, 11, 12, 13, 14, 15, 16, 17]. In general, the decommissioning of offshore wind projects can be divided into three different phases; firstly, the preliminary work to plan the programme and achieve the required permits; this is then followed by the process itself which corresponds to the removal of the components (turbines, foundations, etc.); and finally the monitoring phase that will check that the site is left as it should [14]. While the older publications [13, 17] offered a theoretical description of the process from a technical point of view, recent contributions have been able to extract conclusions from the comparison to the actual experiences in Europe. This way, Topham and McMillan concluded that the initially planned duration and costs are not adequately captured as part of the planning activities, and recommend considering the decommissioning process from the initial development stage of an offshore wind project [5]. Furthermore, complications can also be the cause for radical changes to the levelised cost of energy and for the owner's business case [12]. Finally, Jensen highlights the uncertainty surrounding the process due to the differences between sites in terms of turbine size, location, foundation type, water depth or distance to shore, where again, planning is found to be crucial for an optimised outcome [11]. It is therefore clear that the complexity of the offshore environment, the higher variability between projects, and the lack of experience makes planning and risk identification essential for the successful decommissioning of offshore wind farms.

## 4. Challenges encountered in the decommissioning of offshore wind farms

From the few existing experiences, the decommissioning process is found to be affected by high uncertainties and many unexpected challenges. Based on the literature available, the most important challenges have been reviewed and gathered into four main aspects: the regulatory framework, the planning of the decommissioning process, the logistics and vessels' availability, and the environmental impact. The high variability between projects might difficult the preparation of a general guideline for the decommissioning of offshore wind farms. Nevertheless, regrouping the challenges encountered in a set of key aspects to be tackled may ease a draft of recommended practices. The identified major challenges are summarised in Figure 2 and are detailed in the following sections.

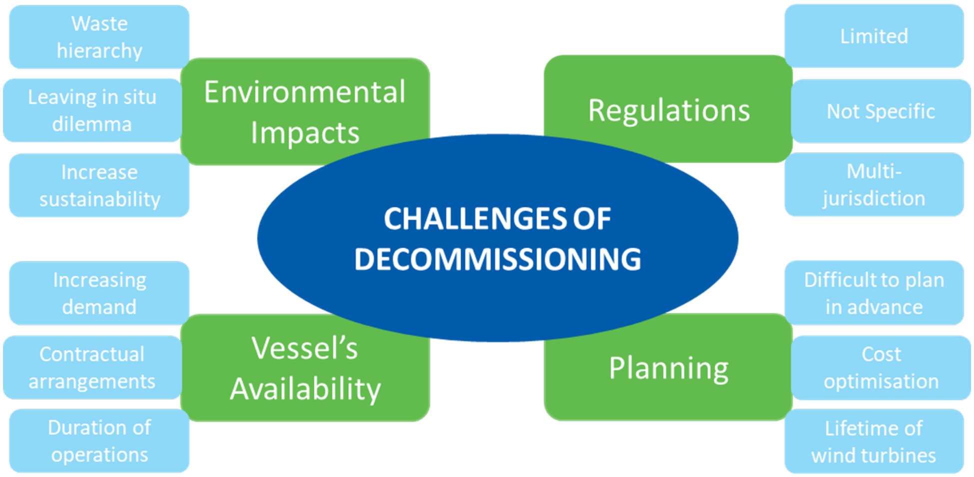


**Figure 2.** Summary of the major challenges encountered during the decommissioning of an offshore wind farm.

### *4.1. Regulatory framework*

The decommissioning process for the whole offshore industry is currently insufficiently regulated and lacks relevant guidelines for recommended practices. This problem is not unique for the offshore wind industry but does also affect other sectors, such as the oil and gas. Moreover, it has to be noted that this limited and vague current available practices are mainly based on oil and gas projects due to the synergies encountered, and often do not apply to renewable energy projects.

A first overview of the regulations concerning the decommissioning of offshore wind farms can be found in [18]. The authors highlight the importance of guideline elaboration as part of the European Maritime Policy, and recommend the total removal of any offshore installation, unless there are strong reasons not to do so. The obligations of offshore wind farm owners in the UK regarding the decommissioning of the installations are contained in [19]. From these regulations, a decommissioning programme is required in the UK from developers to gain their construction approval. This plan includes a description of the operations that would need to take place together with their cost implications. Nonetheless, the detailed programmes are found to be rather simplistic and the costs underestimated [5]. Both aspects may lead to lower rates of return and to non-sustainable decommissioning solutions. Additionally, no prescription is indicated on what needs to be removed; the decision between partial or total removal would be made based only on economic reasons. Kaiser and Snyder elaborate on the bonding requirements for offshore wind farms and on the owner's liability in [17, 20], and also highlight the lack of specific regulations.

It can be easily concluded that the decommissioning phase of offshore wind farms currently lack a specific regulatory framework. Apart from limited existing regulations, the polluter pays' principle is the only strong guiding principle, where any damage done to the environment will need to be remediated by the owner [5]. Thus, the elaboration of specific guidelines is strongly recommended including precise liabilities for the owners.

### *4.2. Process planning*

As previously mentioned, the decommissioning procedures should be planned within the design phase of a project. The process management should allow owners to answer what needs to be done and its duration. Implicitly, decommissioning planning is strongly related to costs.

The necessary activities to be performed are detailed in several contributions [5, 10, 11, 12, 13, 17, 21, 22]. From the literature, it can be noted that planning the decommissioning phase is far from being easy as there is no a unique option. The decisions are determined by the project's characteristics, such as the distance to the operating ports, the water depth, the turbine size or the type of foundation. Nevertheless, other aspects such as duration of the working time offshore, the environmental impacts and the total dismantling costs will also impact the decision significantly. Based on [21], the selection of a specific dismantling method almost always will lead to technical problems.. The number of planned vessels might also affect the cost and duration of the decommissioning phase [22], as well as other unplanned aspects such as the weather. Additionally, the wide spectrum of decommissioning possibilities includes options for full or partial removal of the asset. As no regulations are currently applicable, the decision is mainly driven by economic reasons.

The options for the electric infrastructure and the gravity base foundations are also largely unexplored. While wind turbines have a designed life time of 20-25 years, cables could last for 50 years [23] and gravity foundations for 100 years [12], although there is little experience to confirm these numbers. The importance of this part of the infrastructure may even affect the operation and decommissioning of the whole asset. For instance, the Nysted project that was commissioned in Denmark in 2003, considered an estimated life for both the foundations and the electrical system of 50 years [24]. This is a real example of adequate planning, since for this project the seabed can be leased for twice as long the usual (40 or 50 years instead of 20 to 25) [25]. This approach is currently observed in many decommissioning programmes in the UK.

From an economic point of view, several life cycle models can be found in the literature [26, 27]. Both highlight the high uncertainty affecting the planning and cost estimation due to the lack of experience and real data, and hence, the impossibility of validating assumptions and models. Indeed, based on the few experiences, the process duration and costs do not seem to be effectively captured in planning activities [5]. This uncertainty is slightly considered in [26] by following a stochastic approach for the lifecycle model, including several sources of uncertainty such as the vessels or technician's availability.

Another important aspect is the moment when the decommissioning process will happen. Since its planning should be made a decade in advance, substantial changes regarding the technical feasibility may arise within that timeframe. On the one hand, decommissioning might occur earlier than planned as a consequence of the lack of spare parts required for continuing operation. This was the case at the Lely wind farm, that had to be decommissioned since repowering was discarded due technical obsolescence [9]. Similarly, site dismantling can also happen later than expected if lifetime extension is found to be profitable and technically feasible by the end of the 20-year planned service life [3]. On the other hand, the technical feasibility of the decommissioning process may also be affected by time. Certainly, the equipment, technologies or procedures that were initially planned can become outdated as the time to proceed arrives; conversely, new techniques can also arise and hence ease the general process. As a result, the initial plan for the decommissioning process should be reviewed every few years to keep it technically updated and to include any modifications made to the project that could affect its implementation [16].

Finally, some recent attempts have been made to plan and improve the whole process. An optimisation model is proposed in [10]. The model aims to enhance the decommissioning scheduling in order to minimise the costs, considering inputs such as the tasks to be performed, the vessels' availability, duration or the required expenses. Similarly, a framework for identifying the most appropriate decommissioning method for a given offshore wind farm is presented in [28]. These recent works set out the basis for further work to facilitate the decommissioning planning for practitioners in the field.

### *4.3. Vessels' availability*

Specialised vessels with heavy lifting and specific stability characteristics are required for the performance of the decommissioning operations. However, the vessels also need to adapt to the site conditions. The number of turbines, the foundation type, the water depth, the distance to the operating ports and the seabed type need to be considered, as not all the vessels work under the same conditions nor have the same speed. Even though there are numerous vessels that can be chartered [20], their availability can be compromised due to the demand forecasting of new offshore installations expected in the upcoming years [29], operation and maintenance procedures within already operational projects, and the decommissioning oil and gas facilities as a consequence of the sector synergies found. To avoid this potential bottleneck, contractual arrangements must be ensured largely in advance. Recent contributions also suggest the use of new vessels able to handle very large platforms where the inherent risk of cranes will be removed [30]. Nevertheless, this will not eliminate the competition between installation and decommissioning activities.

Concerning the costs, the vessels' availability accounts for a very large part of the total decommissioning costs. In general, the deck capacity, the working versatility, or the speed will determine the price. To reduce extra costs, the duration of the operations must be meticulously studied. Vessel's operations are not only impacted from high daily rates but also depend on important sources of uncertainty, such as the equipment used, the weather, and the market. Therefore, a best practice would involve a strategy with the least amount of offshore lifting and operating time, leading to reduced costs and risks. This practice is supported in [22], where the total duration and consequently costs, can be reduced by a 6% only by adapting the number of vessels.

### *4.4. Environmental impact*

One of the most controversial topics around the decommissioning of an offshore wind farm is the impact in the marine environment, as detailed in [31]. Two important aspects need to be considered in this regard.

First, the big debate between the need of a total or partial removal. While there seems to exist the belief that leaving the site practically as it was before the project was implemented, recent contributions emphasise the environmental benefits of only partially dismantling an offshore wind farm. Concerning the electric infrastructure, the subsea cables are usually buried between 1 to 2 meters [32], and therefore could be left in situ. Their complete removal would require excavation and pulling out of the trenches and given their extensive length, this would produce an important marine disruption, as well as notable costs. Similar arguments are found for the substructures. A 'renewables-to-reefs' programme is proposed in [13], where the environmental and economic benefits of a partial removal are shown, as opposed to complete removal, especially if the habitat created on the left structures has conservation or commercial value. Substructures could definitely become habitats for marine wildlife, such as fish or crustaceans, as presented in [33]. Oudman also suggests partial removal as more beneficial than complete, and strengthens the idea of turning already existing jackets in artificial reefs, as an example of a green decommissioning. Similar conclusions are provided in [34, 35] where biodiversity enhancement, provision of reef habitats, and protection from bottom trawling are negatively affected by the complete removal of offshore wind farms. All the contributions also highlight the strong link between the regulatory framework and the environmental impacts.

Secondly, to perform a decommissioning strategy as sustainable as possible, this should involve reusing (if possible) or recycling measures. Wind turbines are mainly fabricated with metals, so about 95% can be recycled (mainly from the tower, the gearbox, the main shaft, the generator, castings, bearings and parts from the nacelle and hub) [36]. While there is extensive experience in its recycling, an optimization of the transportation to the recycling plants could enable a cost reduction [36]. The remaining 5% involves power electronics, lubricant and cooling substances, and polymers, which mainly come from the blades and are currently non-recyclable [37]. Blades are certainly the biggest challenge encountered within its material recyclability and transportation logistics perspectives [36]. Any interested readers in the topic are referred to [11, 36] for more detailed reviews of recycling offshore wind farms.

Finally, as concerns the evolution of offshore wind turbines recyclability, it is likely to be negatively affected by the growing size of wind turbines. Indeed, the amount of raw materials required for two small wind turbines is found to be lower than a bigger turbine, equivalent in terms of rated capacity [36]. As a result, the current trend towards installing larger offshore wind turbines will imply a much more important use of raw materials, compromising the sustainability of the subsequent decommissioning process.

## 5. Conclusions

This paper explores the state of the knowledge regarding the decommissioning process of offshore wind farms in Europe. From the limited existing experiences, it is clear that wind turbine end-of-life scenarios and particularly, decommissioning, are affected by high uncertainties. In addition, the complexity of the offshore environment, the high variability between projects, and lack of experience makes planning and risk identification essential for the successful decommissioning of these projects. As a result, the major challenges encountered during this process are identified and individually analysed, namely the regulations, the planning of the process, the vessels' availability and the environmental impacts.

The decommissioning phase of offshore wind farms currently lack a specific regulatory framework. This negatively affects concepts such as liabilities, but strongly impacts other fields like the planning of the process and the resulting environmental impacts. Offshore wind farm owners lack specific guidelines that could help ease their decommissioning planning, that should ideally be included as part of the development phase. With regards to the environmental impacts, the absence or limited dedicated maritime regulations may lead to decisions that can harmfully disturb the marine environment. As a result, the elaboration of specific regulations and guidelines is strongly recommended including precise liabilities for the owners. Concerning the planning, the ideal guidelines should help the owners with the decision about what needs to be done, estimating the decommissioning costs and ensuring that potential technical modifications arisen over time are adequately monitored and considered in the initial plan. The availability of appropriate vessels is also found as a potential bottleneck; decommissioning programmes might compete with new installation activities, operation and maintenance procedures or decommissioning oil and gas facilities, which all require similar vessel characteristics. Again, anticipation is key to ensure adherence to planned duration and costs, together with reduced risks. Finally, the environmental impacts of a partial removal of the asset together with a proper recycling strategy could be the ideal combination for achieving a sustainable decommissioning. Approaches for blade recycling could as well diminish the wind energy carbon footprint and make the process even more sustainable.

Further research should aim at tackling the challenges identified. The assessment of the uncertainty affecting the whole decommissioning process should also become a priority, to allow a proper scheduling, to minimise expenditures and to mitigate risks. Certainly, the decommissioning phase, such as other wind turbine end-of-life scenarios, is affected by important sources of uncertainty. Nevertheless, the complexity of the offshore environment, the diversity of the site characteristics and the limited experience compared to onshore, makes the decommissioning of offshore wind farms more critical. Furthermore, possibilities for blade recycling need to be explored to achieve more sustainable alternatives.

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