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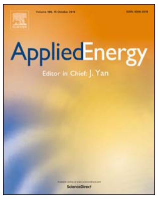

Offshore wind farm repowering optimization

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HIGHLIGHTS

- An optimization strategy for repowering offshore wind farm is proposed.
- The reconstructed wind farm could be with mixed hub height wind turbines.
- The *LCoE* of wind farm was reduced by 10.43% by proposed method.

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ABSTRACT

Decommissioning is usually the last stage of the offshore wind farm life cycle. Due to the challenges of the decommissioning process, such as the impact on the marine environment, severe weather conditions, vessel limitations and lack of operational experience, the decommissioning strategy should be planned to avoid complications, which ultimately can cause radical changes to the levelized cost of energy (*LCoE*) and the wind farm owner's business case. Instead of dismantling, repowering may be a sustainable alternative solution to extend the lifetime of a wind farm. In this paper, the research is focused on optimization of offshore wind farm repowering, which is one option for the wind farm owner at end of life for the offshore wind farm. The *LCoE* is used as the evaluation index to identify whether it is economical to invest in such a way. In an optimized repowering strategy, different types of wind turbines are selected to replace the original wind turbines to reconstruct the wind farm, which is demonstrated to be better than the refurbishment approach which replaces the old wind turbines with the same type. The simulations performed in this research reveal that the reconstructed wind farm, which consists of multiple types of wind turbine, has a smaller *LCoE* (10.43%) than the refurbishment approach, which shows the superiority of the proposed method. This research contributes an optimization tool to the wind industry, which consequently drives down the cost of energy produced by offshore wind turbines.

1. Introduction

The history of offshore wind power can be traced back to 1991 when the first offshore wind farm, Vindeby, was installed in Denmark [1]. Compared with onshore wind power, it is still a novel energy technology and thus more attention has been paid to increasing energy production efficiency or improving installation technology while wind farm owners have seemed to disregard the significance of decommissioning [2]. Likewise, most existing research has concentrated on the development, construction, and operational stages of offshore wind farms [3]. In [4–8], the wind farm micro-siting optimization problem (WFMOP) was investigated. Due to the extremely nonlinear characteristic of the wake effect which is the dominant factor to be taken into account when solving the WFMOP, a heuristic algorithm was widely adopted [4–7] while a recent work [8] also proposed a sequential convex optimization method to solve the WFMOP. Submarine cables are one of the important components in an offshore wind farm, in order to minimize the investment in cables, the cable connection layout is optimized in [9,10]. In addition, some work has also been presented describing offshore wind farm control optimization [11–13], which can increase power production by tuning the pitch angle or rotor speed ratio. However, considering the increasing demand for decommissioning in the near future, decommissioning should be studied and planned at the very beginning of the project to prevent complications which may incur unexpected higher costs and environmental impact [14].

Decommissioning is considered to be the last step of the project. According to [15], decommissioning can be defined as the reverse of

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Table 1
Offshore Projects with more than 10 years of operation [18].

Project name	Country	Wind farm size	Wind turbines
Arklow Bank 1	Ireland	25.2 MW	7
Barrow	United Kingdom	90 MW	30
Blyth	United Kingdom	4 MW	2
Bockstigen	Sweden	2.5 MW	5
Breitling Demonstration	Germany	2.5 MW	1
Ems Emden	Germany	4.5 MW	1
Frederikshavn	Denmark	7.6 MW	3
Horns Rev 1	Denmark	160 MW	80
Irene Vorrink	Netherlands	16.8 MW	28
Kentish Flats 1	United Kingdom	90 MW	30
Lely	Netherlands	2 MW	4
Middelgrunden	Denmark	40 MW	20
North Hoyle	United Kingdom	60 MW	30
Nysted 1	Denmark	165.6 MW	72
Ronland	Denmark	17.2 MW	8
Sakata	Japan	16 MW	8
Samso	Denmark	23 MW	10
Scroby Sands	United Kingdom	60 MW	30
Setana	Japan	1.32 MW	2
Tuno Knob	Denmark	5 MW	10
Utgrunden 1	Sweden	10.5 MW	7
Vindeby	Denmark	4.95 MW	11
Yttre Stengrund	Sweden	10 MW	5

the installation phase; the objective of decommissioning is to return the site to its condition before project deployment as far as possible. The first offshore wind farm decommissioning on record (the Yttre Stengrud wind project) happened in 2016 [17]. This project only operated for 15 years [16]. However, due to the difficulty of finding spare parts and huge cost of repairs and upgrades, the wind farm owner decided to dismantle it [17]. Recently, several decommissioning plans were also announced at Vindeby and Lely. In addition, it is expected that offshore wind farm decommissioning will surge in the next decade since many offshore projects commercialized in the early 2000s. The information in Table 1 shows the operating offshore wind farms which have been in commission for more than 10 years, with the installed capacity for each wind farm (MW).

From Table 1, it can be easily seen that the decommissioning era is coming, and with great variety in the number of wind turbines (WT) and capacity of each wind farm. Taking into account the differences in foundation type, weather conditions, seabed conditions, etc., the decommissioning schemes are expected to be exclusive to and unique for each wind farm. In other words, it seems impossible to put in place a general method for offshore wind farm decommissioning [14]. In order to reduce the impact of the offshore wind farm on the local marine environment, the wind farm developer should follow legal obligations, as in UNCLOS (United Nations Convention on the Law of the Sea) [19], the Energy Act [20], and the Coast Protection Act [21]. All the obligations emphasize the responsibility of the wind farm owner to conduct a complete dismantling, which includes removing the foundation and cables (sometimes cables can be left in situ), to minimize the project's impact on the marine ecosystem, despite findings from the oil and gas industry that keeping concrete foundations harms the ecosystem less than removing them [22]. As a reaction to the environmental impact of constructing and dismantling offshore WTs, research has been conducted on the increased environmental cost of decommissioning of offshore WTs when compared to the onshore counterparts [23,24]. Further studies have even included strategies for decommissioning of foundations and cables in order to limit the impact on local marine life [25]. As an example, Northern America is expected to become a large offshore wind market, and there is already a study is estimating decommissioning costs and proposing strategies ensuring the decommissioning of WTs, foundations, and cables [26].

In the above description, decommissioning has been defined as the process of dismantling the entire wind farm including removal of the foundations, removal of the WTs and cables, etc. However, some components of the wind farm usually have a longer lifetime. For instance, the foundations can last over 100 years (for gravity based foundations) [27] and the internal array and transmission cables can be used for more than 40 years [28]. In addition, a two-year period of monitoring and remediation is required to ensure that the site returns to the state before wind farm construction [29]. Hence, some wind farm owners may decide to repower the offshore wind farms to continue to use the majority of the original electrical system (and/or foundations) to install bigger WTs or change some components, such as drive trains or electronic devices which can improve the production efficiency. In [30], three end-of-life scenarios for offshore wind turbines were summarized as life extension, repowering and decommissioning, and it was pointed out that failure mode identification throughout the service life of an offshore wind farm is necessary for the end-of-life decision. In [14], two repowering strategies: partial repowering (refurbishment) and full repowering were introduced. Partial repowering is the process of installing minor components within the wind farm such as rotors, blades, gearboxes, etc., which is similar to life extension as described in [30]. Full repowering involves replacing the old turbines with newer, bigger ones to obtain higher energy efficiency. Repowering is considered as one end-of-life decision for an offshore wind farm in [2,3,14,19,25,27–36]; it is sustainable and there is potential value in recycling or reusing the dismantled spares. It has become an increasing common practice for Germany and Denmark [31]. Different repowering options considering the Spanish regulatory framework were analyzed in [32,33] for two existing wind farms - Bustelo and San Xoan. An economic analysis of wind project repowering decisions in California was conducted using the common evaluation index *LCoE* in [34]. In [37], the profitability for full and partial repowering was analyzed using net present value (*NPV*) as the evaluation index. It concluded that full repowering would be attractive after 20–25 years of operation, while before this time the benefits of repowering are insignificant. Moreover, partial repowering shows only about 10% cost savings compared with full repowering, so it is not preferable unless advanced technology can be applied to promote generation efficiency or minimize operating costs. Nevertheless, not all WTs will be decommissioned at the exact same time as assumed in [37]. Several studies have been conducted on the decommissioning of oil and gas rigs with a special focus on avoiding damage to the local marine environment [38,39]. However, since oil and gas is a limited resource, reuse-in-place of facilities and potential optimization of this was not touched upon in these studies. One lesson learned, however, is the fact that the least damage is done to the marine environment by keeping the concrete structures under the sea [22], instead of removing them, which only strengthens the proposals of this research paper. A number of attributes are relevant in particular to repowering, such as the cost of infrastructure, the environmental aspects, the regulatory framework, the logistics, insurance, etc. However, in this paper, we focus on the economic analysis of the full repowering option using an optimization method. The wake effect is the dominant factor considered and the relation between energy production and additional investment is investigated. The replacement of merely one WT within a wind farm may cause changes in the wind conditions observed for the other WTs, due to changes in wakes. It is therefore worth considering which WTs to remove and which types of WTs to install to maximize the energy output of the whole wind farm. In this research, both bigger WTs and smaller ones are considered for full repowering. However, different WTs would have a different hub height and blade diameter compared with the original one. The wake losses in such a mixed hub height wind farm should be estimated so that the profitability of the repowering decision can be properly analyzed.

The contributions of this research can be summarized as follows:

1. The repowering option for an offshore wind farm was formulated as a non-convex optimization problem and solved by heuristic optimization algorithm. Though the heuristic algorithm has been widely