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Innovative alternatives for repowering offshore wind farms

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Innovative alternatives for repowering offshore wind farms

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Abstract. To deliver a climate neutral Europe by 2050 there is an unprecedented urgency to decarbonise Europe's electricity supply. The offshore wind industry is gearing up to this challenge with an increase in the rate at which high generating capacity offshore wind farms (OWFs) are deployed. Innovative repowering integrates early decommissioning and repowering of OWFs by using future large wind turbines (WTs, e.g. 20 MW WT). First-of-its-kind case studies have been presented to quantify the increased power generation capacity and the levelized cost of energy (LCOE) of repowering two OWFs with fixed and floating foundations. The repowering alternatives have been compared with the base case scenario (which involves decommissioning after the design life of 20 years) and the lifetime extension scenario (decommissioning in 25th year). The case studies show that a significant increase in energy output could be coupled with a reduction in the LCOE using the same OWF sites. The capacities of the OWF with fixed and floating foundations have been increased by 2.5 times (317 MW to 800 MW) and 2 times (400 MW to 800 MW) by repowering, respectively. Compared with developing an OWF on a new site, repowering has the potential to significantly accelerate the current installation capacity. Repowering has the potential to provide a competitive alternative to the lifetime extension of OWFs. Furthermore, the OWF with floating foundations has greater LCOE reductions compared with the OWFs with fixed foundations. This study has also provided evidence that enabling technologies and collaboration with other sectors would reduce the environmental impacts and costs of decommissioning of OWFs. This paper has suggested a way forward for research and development to overcome both technological and non-technological barriers to unlock the potential benefits of innovative alternatives of repowering OWFs.

Keywords: Offshore wind farm, decommissioning, repowering, levelised cost of energy, reuse, fixed foundation, floating foundation.

1. Introduction

There are many challenges in achieving WindEurope's announced target production capacity of 450 GW from offshore wind farms (OWFs) in 2050 [1]. Two key challenges to reach the target lie in efficiently utilising European seas and further reducing the costs of OWFs. The current technology development has focused on extending the lifetime of OWFs (e.g. from 20 years to 25 years). However, the OWFs which have achieved high operational capacity factors will result in high operational and maintenance costs towards the end of their lifetime (i.e. from 15 to 25 years). This study proposes innovative repowering concept which integrates early decommissioning and repowering OWFs by using future large wind turbines (WTs, e.g. 20 MW WT) to achieve higher power generation within the same ocean space (e.g. to double or triple the power generation). Repowering also offers the potential to accelerate the rate at which high (generation) capacity OWFs are installed; several times faster than developing a new OWF which must follow the process of leasing, consenting, financial close and installation. The point at which the developers start preparing new sites will typically begin approximately nine years before the OWF is installed [1]. However, the benefits of repowering OWFs depend on the technology advancements in many sectors, including decommissioning and installation, operation and maintenance (O&M), in the development of large wind turbines, and early planning during the new OWF design phases.

The OWF industry is an emerging sector which has resulted in the design stages providing insufficient planning for the decommissioning phases. Consequently, this decommissioning will not be cost effective and have a high environmental impact. This study proposes enabling technologies from other sectors (e.g. offshore oil/gas industry) and other collaborations (e.g. partly reusing OWF structures for artificial reefs) to reduce the environmental impacts and costs associated with the decommissioning of OWFs.

Several OWF developers have explored the potential of using repowering in their recent EU H2020 collaborative proposals. Currently, however, there is little research and business activity around repowering [2]. The goal of this paper is to propose and explore new ideas to progress OWF decommissioning and repowering. It also suggests new possibilities when repowering floating OWFs. The preliminary results presented in this paper are from a collaborative study between industrial and academic partners [3] which show the potential of repowering for two OWF versus lifetime extension scenarios. The objective of this paper is to inspire research and technological development in decommissioning and repowering, and to contribute to both the design of new OWFs and operation of existing OWFs.

2. Reducing the environmental impacts and costs of decommissioning OWFs

In order to unlock the potential benefits of repowering OWFs, it is crucial to reduce the environmental impacts and costs of decommissioning. The current reuse or recycling solutions for the components of decommissioned OWFs are mainly utilised onshore. This study suggests a number of innovative offshore approaches including: i) enabling technologies from other sectors, ii) partly reusing OWF structures for other sectors, and iii) increasing the reuse of old OWF infrastructure within a new OWF.

The experiences and lessons learned from the decommissioning of both the first OWF in Denmark in 2017 (Vindeby OWF, 1991-2017) [4] and the planning of the world's first megawatt floating wind turbine (Hywind Demo, 2009-present) [5] have shown that the decommissioning of an OWF is expensive and also has a high environmental impact. However, decommissioning technology along with costs for OWFs remain largely unknown and mainly depend on designs and site conditions.

For an OWF employing fixed foundations, the innovations related to a reduction of the environmental impact of decommissioning and associated costs include three aspects. The first lies in transferring the decommissioning experience from the offshore oil and gas (O&G) industry to the OWF sector, such as applying cutting techniques from oil and gas platform decommissioning to replace hammering, which was used for the removal of the Vindeby OWF [4]; underwater cutting of large cylinders (e.g. monopile foundations) requiring further exploration. The new challenges for OWFs are related to the significantly greater number of structures to be cut (a typical OWF has about 50 to 100 wind turbine (WT) units) and a lower decommissioning budget when compared with the O&G sector. Secondly, investigating the potential of partially reusing old OWF structures for other sectors (e.g. artificial reefs), which should follow regulations (e.g. the North Sea Principles [6]). The case which partly reuses OWF structures has been compared with a strict total removal policy [2]. Thirdly, the optimisation of OWF planning and designing to increase the reuse of old OWF infrastructure by a new OWF, which may place greater emphasis on standardisation and modular structures.

A floating offshore wind turbine (FOWT) will offer new advantages of decommissioning and repowering. The decommissioning method is assumed to be the reverse of the installation. The current base case includes the following three major steps:

- cut, disconnect and retrieve the infield cables and the dynamic part of the export cable,
- disconnect the mooring lines and tow the FOWTs to shore for decommissioning at a certified yard, and
- disconnect the mooring lines from the anchors.

For example, if the floater is a concreate structure (see Figure 1) and it has a lifetime of 50 years, it could be reused for new OWFs after the decommissioning. One idea is to combine three floaters of an 8 MW FOWT to form the new floater for one large 20 MW WT. There are ideas to reuse the mooring lines including the anchors, in addition to infield and export cables. However, no engineering designs and feasibility studies have been carried out.

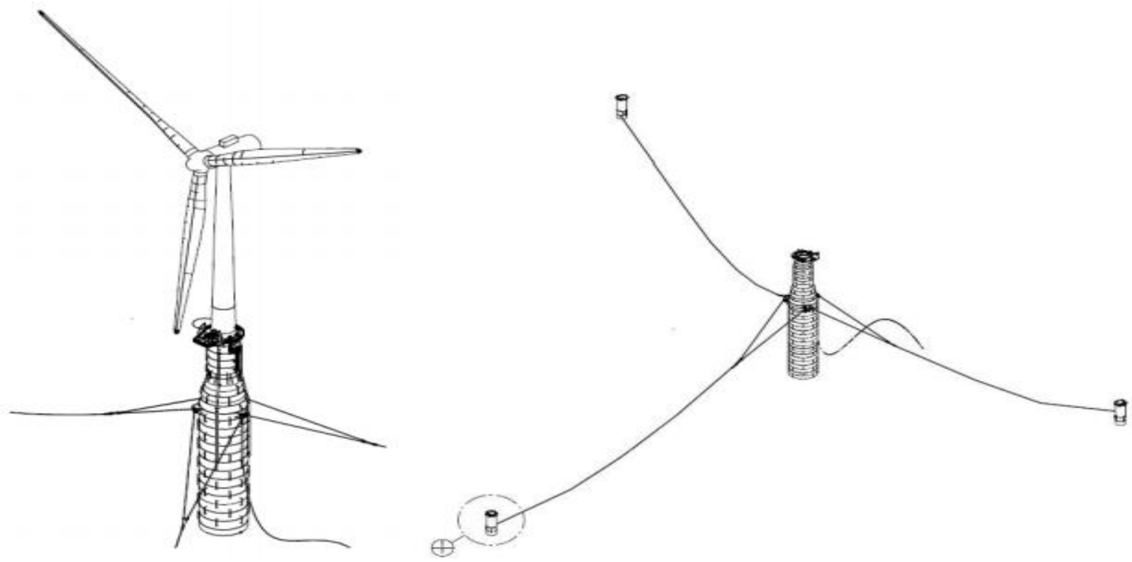

Figure 1. Illustration of the FOWT with three mooring lines and three anchors [5].

3. Setting-up study cases

FOWFs will be pivotal in reaching WindEurope 450 GW target and their repowering offers many new advantages over OWFs with fixed foundations. Accordingly, repowering OWFs with both fixed and floating foundations will be addressed. The three study scenarios are shown in Figure 2 and the assumptions for Scenarios 1 and 2 are that there is no replacement of the OWF at the end of its life. The scenarios apply to a single OWF developer. Although it is likely that a new OWF will be developed on the site of an old farm, it is presumed that this will happen with different developers.

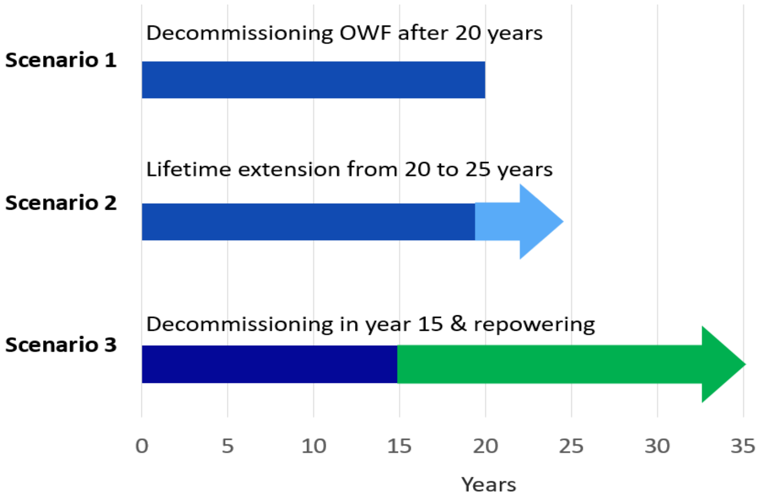

Figure 2. Three scenarios for OWFs with both fixed and floating foundations.

3.1 A comparison of three scenarios for OWFs with fixed foundations

Firstly, under Scenario 1, the OWF with fixed foundations has 88 units of 3.6 MW WTs and will be totally decommissioned after 20 years. This base case is from a real OWF which started operating in 2012 and has a site area of 35 km^2. Secondly, Scenario 2 lies in extending the lifetime of the OWF from 20 years to 25 years and totally decommissioning it afterwards. Thirdly, Scenario 3 involves innovative integration of early decommissioning (in the 15th year) and repowering; it proposes to use 40 units of 20 MW WTs to replace 88 units of 3.6 MW WTs. The total electrical power generation capacity will be changed from 317 MW to 800 MW using the same site (see Figure 3). The repowered 40 units of large 20 MW WT will operate for 20 years.

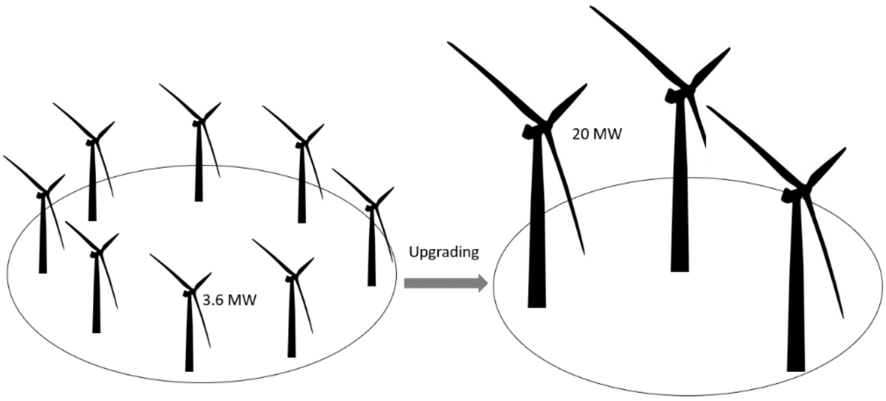

Figure 3. Decommissioning and repowering existing OWF by using larger WTs.

3.2 A comparison of three scenarios for FOWFs with floating foundations

Three similar scenarios have also been investigated for an FOWF. Firstly, under Scenario 1, the farm with 400 MW (50 units of 8 MW) has a design life of 20 years. Secondly, Scenario 2 extends the lifetime from 20 years to 25 years and decommissions the FOWF afterwards. Thirdly, Scenario 3 involves innovative integration of decommissioning and repowering; it will use 40 units of 20 MW

FOWTs to replace 50 units of 8 MW, whereby the total electrical power generation capacity will be doubled from 400 MW to 800 MW using the same site.

4. Implementation case studies

4.1 LCOE Model

Megavind's levelised cost of energy (LCOE) model [7] has been widely used by engineers when developing OWFs. It is a specialised wind farm open-source analysis tool and is based on the LCOE calculation experiences from many OWFs. It has been designed to calculate the LCOE under the various income and spending streams for each year or month during the life cycle of a specified farm. Accordingly, the Megavind's LCOE model has been used to calculate the LCOE of the cases studied in this work and it is given as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where the terms are
I_t, investment expenditures in year t;
M_t, operations and maintenance expenditures in the year t;
F_t; fuel expenditures in the year t;
E_t, electrical energy generated in the year t;
r, discount rate; and
n, expected lifetime of the system.

The structure of the LCOE model of Megavind is given in Figure 4.

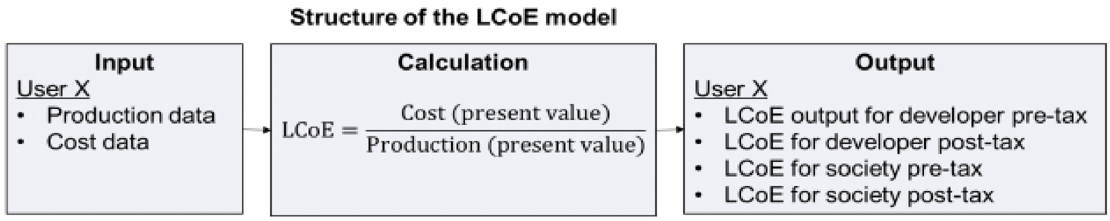

Figure 4. Structure of Megavind's LCOE model [7].

4.2 Assumptions

The major assumptions introduced for the Megavind LCOE calculations of the OWF with fixed and floating foundations are listed in Table 1.

Table 1. The major assumptions for LCOE calculations.

	OWFs with fixed foundation	OWFs with floating foundation
Assumptions for all three scenarios	▪ Capacity coefficient of 0.4 for both 3.6 MW and 20 MW WTs. ▪ The OWF wake losses are assumed to be a small percentage of the total production. ▪ The same electricity price for each year. ▪ Norwegian corporate tax rate: 22%.	▪ Capacity coefficient of 0.4 for both 8 MW and 20 MW WTs. ▪ The FOWF wake losses are assumed to be a small percentage of the total production. ▪ The same electricity price for each year. ▪ Norwegian corporate tax rate: 22%.
Assumptions for Scenario 3	▪ No electricity production period due to decommissioning and repowering construction: 12 months. ▪ No reuse (10% and 20% of the old OWF infrastructure can be reused for the new OWF, see Appendix).	▪ No electricity production period due to decommissioning and repowering construction: 6 months. ▪ No reuse (30% and 50% of the old OWF infrastructure can be reused for the new OWF, see Appendix).

4.3 LCOE calculation results

The case study includes calculations considering development expenditure (DEVEX), capital expenditure (CAPEX), operational expenditure (OPEX) and abandonment expenditure (ABEX) of the fixed and floating OWF cases using the Megavind benchmark computation [7]. The ABEX values do not extend to include complete life cycle cost analyses (LCCA) for life cycle assessments (LCA) of cradle-to-grave or cradle-to-cradle scenarios which could include the alternative criteria of: dismantle and recycle, dismantle and reuse, refurbish and sell, or sell. There are many uncertainties in the cost data input for the LCOE calculation. For the base case of the OWF with fixed foundations, this calculation has used input data from an existing OWF. The relative LCOE, compared with their respective base cases, have been presented in Tables 2 and 3. Additionally, sensitivity analyses have been performed on the LCOE input values in this work [3]. For Scenario 3, the effect on the LCOE of considering reuse alternatives and the various investment assumptions for new OWFs is discussed in the Appendix.

The results are shown for both the fixed (Table 2) and floating (Table 3) OWFs. The Scenario 3 results are presented for the case of 20, 25 and 35 years so that a more meaningful comparison can be made with Scenario 1 (20 years) and 2 (25 years) results.

In Table 2, for the fixed OWF case, a reduction in the LCOE of 5% can be seen in Scenario 2 compared with the base case (Scenario 1) which confirms that the lifetime extension is effective in reducing the LCOE. In Scenario 3, after 25 years at the same site, repowering will generate 17 TWh more power than Scenario 2 with its lifetime extension. This provides evidence related to the enhancement of the OWF development plan. Scenario 3 displays a relative LCOE of 1.17 due to the decommissioning and repowering costs in year 15. But Scenario 3 achieves a relative LCOE 0.99 with the farm running to the 35th year, under the assumption of no reuse of the old OWF infrastructure for the new OWF. However, for cases considering a 10% and 20% reuse of the old OWF infrastructure by the new OWF, the relative LCOE can reach 0.95 and 0.94 respectively (see Appendix).

Table 2. Comparison of the three repowering OWF cases with fixed foundation.

	Scenario 1. Decommissioning after 20 years (base case)	Scenario 2. Lifetime extension from 20 to 25 years	Scenario 3. Decommissioning & repowering		
Period	20 years	25 years	20 years	25 years	35 years[a]
Power generation [TWh]	22	28	31	45	73
Relative LCOE	1	0.95	1.17	1.09	0.99

[a]Total 35 years consists the original OWF operation of 15 years plus the repowered OWF operation for another 20 years.

Table 3 presents the results of Scenario 3, again at 20, 25 and 35 years; with the FOWF showing a greater LCOE reduction compared to the OWF with fixed foundations. The relative LCOE achieves a value of 0.96 in Scenario 2. After 20 years, Scenario 3 results a relative LCOE of 1.02 due to the decommissioning and repowering costs; although 7 TWh more energy will be produced compared with Scenario 1. After 25 years, Scenario 3 will reach a relative LCOE of 0.99 and produce 14 TWh more energy than Scenario 2. If Scenario 3 runs for 35 years, a relative LCOE of 0.95 is evident. For the cases considering a 30% and 50% reuse of the old FOWF infrastructure in the new FOWF, the calculated relative LCOEs reach 0.91 and 0.89 respectively (see Appendix).

Table 3. Comparison of the three scenarios FOWF with floating foundation.

	Scenario 1. Decommissioning after 20 years (base case)	Scenario 2. Lifetime extension from 20 to 25 years	Scenario 3. Decommissioning & repowering		
Period	20 year	25 year	20 year	25 year	35 year
Power generation [TWh]	28	35	35	49	77
Relative LCOE	1	0.96	1.02	0.99	0.95

4.4 Discussions

4.4.1 Calculated LCOEs and verifications

The study cases have quantified the benefits of repowering fixed and floating OWFs, comparing the generation capacities and LCOE with their base case scenario (which involves decommissioning after the design life of 20 years) and the lifetime extension scenario (decommissioning in 25th year). It was shown that a significant increase in energy output could be coupled with a reduction in the LCOE using the same OWF sites. The capacities of the fixed foundation OWF and FOWF have been increased by 2.5 times (317 MW to 800 MW) and 2 times (400 MW to 800 MW) by repowering, respectively. After 25 years, repowering will generate 17 TWh (fixed OWF) and 14 TWh (FOWF) more electricity than the lifetime extension cases. The relative LCOE of the repowering cases are 0.99 for the fixed foundation and 0.95 for the FOWF when compared with their base cases. The calculated relative LCOE will be further reduced when the old OWF infrastructure is partly reused by the new OWF, and the investment in the new OWF shows cost per kWh advantages given the introduction of large capacity units (with the sensitivity analysis presented in Appendix).

For floating OWFs the results show greater LCOE reductions compared to the fixed foundation designs, since the period of the decommissioning and repowering is expected to be much shorter and the decommissioning costs lower.

Verifications of the calculated LCOEs are limited to a comparison with the base case with fixed foundations; the corresponding real OWF started operation in 2012.

When considering the long process of leasing, consenting and financial close before the installation of a typical OWF, repowering has the potential to accelerate the realisation of a higher capacity farm; which may be in the order of several times faster than developing a new OWF. It should be noted that the LCOE comparisons should only be viewed in terms of their specific context since the assumptions on which they are calculated have numerous simplifications and uncertainties.

4.4.2 The limitations of the LCOE calculation models

The OWF investments represent the largest LCOE component and there are significant uncertainties for new OWF investment including the price for future 20 MW WTs. The change in LCOE from a variation in two assumptions of new OWF investment have been explored in the Appendix of this paper. The assumption in Megavind uses the cost extrapolation to 20 MW, while another assumption based on per watt cost reduction for a large unit of OWF has been added. One should also note that Megavind is a basic engineer's LCOE calculation tool. It uses an annual or monthly average power generation for a WT instead of making calculations using accurate wind speed time series data. Moreover, the wake effect losses of an OWF site based on assumptions instead of calculations.

First-of-its-kind LCOE case studies have been presented establishing a quantitative foundation for the concept of repowering OWFs, which also includes sensitivity analyses related to various reuse and investment assumptions (see Appendix). Further work beyond the scope of this article will include additional sensitivity analyses. When greater knowledge of both the decommissioning and repowering processes are available, the proposed cases should be further assessed by more sophisticated tools. One might alternatively choose the net present value (NPV) to provide the basis of financial comparison between the study cases as it is able to account for the time value of the inherent cash flows. Furthermore, there may be opportunity to sell part of the shares of an OWF to re-finance the early decommissioning and repowering.

4.4.3 The technological and non-technological barriers of repowering

Though the LCOE benefits of repowering seem promising, the feasibility of the repowering solution depends on the acceptance of proposals for decommissioning accompanied by new installations. The commercial decommissioning must follow an Environmental Impact Assessment (EIA) and provide analysis of the baseline physical, biological and human environment. The background information includes: site layout, adjacent facilities, site characteristics, met-ocean characteristics, bathymetry, sea-bed conditions, shipping and navigation, commercial fisheries and protected sites. The decommissioning and repowering of OWFs is currently hindered by both technological and non-technological barriers including i) high environmental risks, ii) lack of decommissioning regulations and technologies, iii) low market volume and shortage of experiences, iv) absence of policy, financial support and regulatory regimes to foster the developers' cooperation across multiple sectors, v) risks when making the operational transition from old OWFs to new OWFs, vi) absence of decommissioning and repowering planning at the early phases of OWF development and design, and vii) uncertainties regarding social acceptance.

5. Conclusions

The innovative repowering two OWFs with future fixed and floating 20 MW WTs have been studied. The cases considered have identified and quantified promising benefits of an innovative integration of early decommissioning, in 15th year, and repowering for fixed and floating OWFs. The repowering solutions have been compared with the generation capacities and LCOE of their respective base case scenario (which involve decommissioning after the design life of 20 years) and lifetime extension scenario (decommissioning in the 25th year). It was shown that using the same OWF sites a significant increase in energy output (approximately double the power generation) coupled with a reduction in the LCOE could be achieved. Furthermore, the OWFs with floating foundations result in greater LCOE reductions compared with the OWFS with fixed foundations.

If decommissioning and installation technology can achieve breakthrough progress with regard to reducing environmental impacts and costs, repowering OWFs has great potential to be a cost-effective solution for OWF developers and provides a new competitive alternative to the lifetime extension of OWFs. The proposed decommissioning innovations include both enabling the technologies and collaborating with other sectors. This study has urged research and business development to overcome both the technological and non-technological barriers of repowering, which mutually contributes to the operation of existing and the design of new OWFs.

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Disclaimer: This paper presents the repowering case studies overseen by Equinor as one of the academic supervisors and does not represent in any way Equinor's OWF development strategies or views.

Appendix: LCOE sensitivity analysis in Scenario 3

This appendix presents the LCOE relative to the base case (Scenario 1) for various degrees of reuse when decommissioning and repowering, and the investment costs of the new OWFs in Scenario 3. The potential reuse of old OWF infrastructure for a new OWF and for other sectors are listed in Table A.1, while the assumptions of the new OWF investment are given in Table A.2.

Table A.1 Potential reusing old OWF infrastructure for a new OWF and for other sectors.

OWFs with fixed foundation	OWFs with floating foundation
The offshore transformer station, in-field cables and transmission cables can be reused, but need to be enhanced according to the new enlarged capacity; Reusing the decommissioned OWF infrastructure for other sectors (e.g. artificial reefs).	
Scour protection rocks	Reusing floaters (e.g. combing three floaters of 8 MW to create a new floater for 20 MW wind turbine; Reusing the moorings and anchors, but need to be enhanced according to the new enlarged capacity.

Table A.2 Two different assumptions of the new OWF investment.

	OWFs with fixed foundation	OWFs with floating foundation
Assumption 1: Same costs per kW	Investment of new OWF infrastructure and installation proportional to the old OWF per kW [8]	
Assumption 2: Cost reduction per watt with the large capacity & costs of new infrastructure and installation related to units	The price of 20 MW WT is 4 times the one of 3,6 MW WT The price of 20 MW foundation WT is 3 times the one of 3,6 MW WT The installation cost of 20 MW WT is 3 times the one of 3,6 MW WT	The price of 20 MW WT is 2.5 times the one of 8 MW WT The price of 20 MW floater is 2 times the one of 8 MW WT The price of 20 MW mooring line system is 2 times the one of 8 MW WT The installation cost of 20 MW WT is 2 times the one of 8 MW WT

It is difficult to quantify the costs of the different reuse alternatives which include both the cost reduction of decommissioning an old OWF and the investment in a new OWF. For an OWF with a fixed foundation the amalgamated cases are: no reuse, 10% reuse and 20% reuse. The 10% reuse case is achievable with the existing OWF design and current technology, while the 20% reuse case will require an improved future design. For FOWFs the combined cases are: no reuse, 30% reuse and 50% reuse. The 30% reuse case is considered achievable with an optimal OWF design utilising current technology, while the 50% reuse case will require radical innovations. The calculation results from Megavind's LCOE model are given in Table A.3. For OWF with fixed foundation, Table A.3 shows that the relative LCOE reaches 0.99, 0.96 and 0.94 for the cases of with no reuse, 10% and 20% reuse respectively. For the OWF with floating foundations, the relative LCOE reaches 0.95, 0.91 and 0.89 for the cases with no reuse, 30% reuse and 50% reuse respectively. OWFs with floating foundation cases show a lower relative LCOE from the higher percentage reuse.

Table A.3 The LCOE varying with different reusing alternatives in Scenario 3 in 35 years.

	OWF with fixed foundation			OWF with floating foundation		
Various reusing alternatives	No reuse	10% reuse	20% reuse	No reuse	30% reuse	50% reuse
Relative LCOE (compared to the base cases in Tables 2 & 3)	0.99	0.96	0.94	0.95	0.91	0.89

The investment cost represents the largest component of the LCOE and there are significant investment uncertainties for new OWFs (e.g. 20 MW WTs and foundations). The LCOE is presented under two further assumptions in Table A.4; namely, i) that the investment costs of new OWF infrastructure and installation are extrapolated to represent 20 MW units [8], and ii) the investment cost of new OWF infrastructure will have advantages to use a large capacity unit (as the costs of new infrastructure and installation are related to the number of units instead of the costs per watt). The table shows that the relative LCOE will be 0.99 and 0.93 under the two assumptions for an OWF with fixed foundations, while the relative LCOE will be 0.95 and 0.87 under these assumptions with floating foundations. The benefit of the lower LCOE from decommissioning and repowering is dependent on the cost reduction provided by the large WTs in the new OWFs.

Table A.4 The LCOE varying with different investment assumptions in Scenario 3 in year 35.

	OWF with fixed foundation		OWF with floating foundation	
Various investment assumptions	Assumption 1: Proportional to the costs per watt [6]	Assumption 2: Advantages with large unit	Assumption 1: Proportional to the costs per watt [6]	Assumption 2: Advantages with large unit
Relative LCOE (compared to the base case in Tables 2 & 3)	0.99	0.93	0.95	0.87

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