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End-of-life planning in offshore wind

EXECUTIVE SUMMARY

Over 3.5GW of global offshore wind capacity will reach its end of operational life by 2035 if no other action is taken. In its efforts to create an alternative source of energy to fossil fuels, the wind industry's focus in its first decades has been to increase deployment and rapidly reduce the costs of energy. Compared to these urgent and immediate priorities, the decommissioning of wind farms after their operational lifetimes was an issue for longer term consideration.

Decommissioning is currently the default option: developers are required to remove all the wind farm parts to restore the seabed in its prior condition. However, the development of offshore wind is accelerating, and the existing fleet is aging, and so the time has come to consider alternative and more sustainable options for offshore wind sites after an approximately 25-year life. Extending lifetime and repowering (upgrading parts of the old asset) maintains or increases the utilisation of the existing assets, often offering higher yields, lower maintenance costs and environmental benefits by delaying and preventing disposal.

A cost-benefit analysis of five end-of-life scenarios was conducted for a representative UK offshore wind farm of 35 turbines (6MW rating) reaching its 25-year operating life in 2040.

The scenarios were:

- Full removal
- Partial removal
- Full repowering
- Partial repowering, and
- Life extension

The results showed partial repowering (a 10MW turbine upgrade) yielding the highest positive cash flows, followed by life extension and full repowering (replacement of foundations and cables). In addition, each scenario required a set of vessels to implement each strategy. The carbon footprint of vessels hired for the completion of each scenario was estimated and showed full repowering having the highest carbon equivalent emissions (2,707 tCO₂e per annum) and life extension the lowest (63 tCO₂e per annum). However, these carbon emissions are minimal compared to the carbon saved from the operation of the wind farm. Larger turbines can save an extra 110 MtCO₂e per year when a windfarm is repowered compared to the same electricity produced from a conventional natural gas plant.

In spring 2021, ORE Catapult is launching its five-year Circular Economy for Wind Sector Joint Industry Programme (CEWS JIP) which aims to collaborate with academia and industry and key policy stakeholders in mapping the material make-up of the wind industry for the coming decades, discussing the blade recycling challenges and opportunities, as well as identifying a road-map for cost reduction, and industry-led best practice and standards for end-of-life strategies.

INTRODUCTION

Renewable energy continues to increase its presence in the global energy generation mix replacing well established fossil fuels. The strong pressure for mitigation of their environmental impact, in combination with the fall in oil demand, has led oil majors to search alternative ways to diversify their operations, embrace energy transition and take action to increase investment in renewable energy projects. However, one common characteristic all assets have, either in oil and gas or renewable energy, is that they age and the volumes of assets and materials to be dealt with responsibly at the end of useful life is striking.

In terms of oil and gas installations located offshore, 2,624 wells, over 1.2 million tonnes of topsides, and almost 675,000 tonnes of substructures will need to be remediated, removed and sealed in the next decade.¹ The current practices allow 98% of the materials to be removed and some limited amount is recycled, however reuse and remanufacturing should be considered closely as the preferable option. Decommissioning spending is estimated at £67 billion in the next decade including £15.2 billion for the UKCS alone.¹ Most of these structures were built in the 1970s with minimal consideration of removal strategies at the end of their life and with decisions taken two to three years before ceasing production. There is a current objective from industry and government to reduce the currently high decommissioning costs by 35%, and at the same time enhance industry understanding of current policies, update legislation and related guidance, and foster sharing of data, good practice and cost-effective compliance.

Onshore wind is facing similar challenges with countries like Germany and Spain having the largest aged fleet, at 16GW and 10GW, respectively. In the UK, 20 onshore wind projects (665MW) have applied for extensions and repowering, mostly located in Scotland, while approximately 1.2GW of new UK onshore wind repowering capacity is under development with around 180MW of repowering projects planning to bid in the 2021 CFD auction.² However, about 80% of the projects have life extension as the preferred strategy and only 10% plan for repowering, mostly due to cost constraints. Although other factors related to permitting bottlenecks, end of subsidy period, environmental

regulation and public acceptance also define the most appropriate decision in each wind farm project, 30% of onshore wind farms could be eligible for repowering. Sharing experience and lessons learned from these two sectors can be beneficial for the future end of life decisions offshore wind developers should make.

THE CHALLENGE

Offshore wind is a newer sector than both oil and gas and onshore wind, but there are apparent similarities in terms of decommissioning their structures. Estimates show that over 3.5GW of offshore wind will reach its end of operational life by 2035 if no other action is taken. There is currently no defined framework on the process that decommissioning should follow, which makes estimation of costs a difficult task affecting future cost reduction potential. Even if decommissioning is so well structured that it can be considered as reverse installation, installation is a costly exercise and lack of experience for dismantling foundations could bring delays, and thus heightened costs.

Currently the majority of installations approaching their end of life are smaller turbines that are placed on thinner monopiles, close to shore and in shallow waters, but the growth of the sector will bring new challenges in the coming years as site conditions will be harsher and existing vessels may not be adequate to meet decommissioning demand, both in terms of volume and specifications. Vessel costs represent 60% to 80% of projected decommissioning costs so project owners need to encourage flexibility in their timeframes to be able to avoid peak periods of high demand.³ New build vessels capable of working in these larger installations should be developed and keep pace with the turbine deployment rate. In addition, offshore oil and gas experience could prove valuable to offshore wind, as oil and gas installations have had to operate in similarly harsh environments and lessons can be drawn about the absence of early planning.

The alternative strategies discussed refer to life extension and repowering (Figure 1). Developers will have to consider these options – replacing with new components where feasible – in more detail during the design phase to be able to plan ahead and make optimal adjustments for cost savings. Currently end-of-life strategies are not fully formed until the project comes close to its end and there is limited regulatory support to guide wind farm developers.

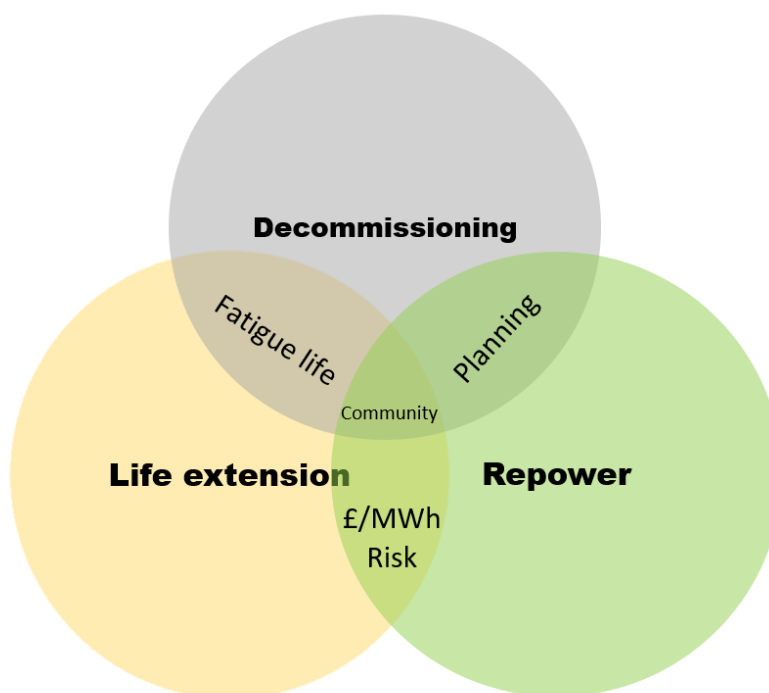


Figure 1 End of life decision-making considerations⁴

Decommissioning is now rising to the top of the offshore wind industry’s agenda with many projects running or in the pipeline worldwide. In particular, ORE Catapult is currently developing an industry-wide programme to cover not only the issues and understanding of what decommissioning will mean, but the wider circular economy impacts that component reuse and material recycling will have. The five-year Circular Economy for the Wind Sector (CEWS) Joint Industry Programme aims to bring together ideas and solutions from different researchers, operators, developers and policymakers for the most sustainable practices that can be adopted at the end of a wind farm’s operating life.

This Analysis & Insights (A&I) paper presents the cost of decommissioning based on the A&I team’s in-house modelling and the end-of-life strategies UK offshore wind farm developers could employ with their aging assets. This paper also shows the results of an analysis comparing different end-of-life scenarios for a UK offshore wind farm by 2040 and gives insights from the developer’s perspective on choosing the optimal strategy, both in terms of cost and vessel carbon footprint.

END-OF-LIFE STRATEGIES

The sustainability and decarbonisation agenda have turned a spotlight onto end-of-life decisions for offshore wind farms, an area that has previously not attracted much attention. The industry has just a few decades of experience to draw upon, while the rapid growth of installations brings

decommissioning and the need for alternative strategies ever closer. There is currently no standard legislation that specifies the best practices after operational life end. Decisions are strongly dependent upon an asset’s physical condition and theoretically admissible lifetime of the turbine, as well as upon the overall cost and site conditions, specific country legislation, logistical difficulties and potential environmental impact. The main end-of-life strategies which are currently known are presented below; however, overlaps can occur so parts of one strategy can be combined with others for a particular wind farm.

Decommissioning

It is estimated that about 600 offshore wind turbines will need to be decommissioned by 2030 with 72% secured in monopiles. Although decommissioning can seem to be a straightforward process, just a reverse installation, there are a range of complications, from high logistical costs to complex seabed conditions. The oil and gas sector is currently facing higher than expected costs for decommissioning its platforms due to initial under-estimates of costs and the lack of early planning we have mentioned previously. In wind energy, wind farm owners agree a decommissioning bond as part of their initial leasing agreement, but the cost can become unrealistic after 25 years or more of asset lifetime. Early consideration of the details is an important factor in selecting the best strategy in each case. Offshore wind developers look at adapting the most cost-effective options, ranging from complete turbine removal to leaving in situ.

After undertaking a decommissioning assessment, the main steps of the process include preparation, actual removal of turbines, substructures and electrical equipment, transportation to port, handling of waste following the waste hierarchy (reuse/recycle/dispose) and the material processes described earlier. Estimated costs for decommissioning a 400MW offshore wind farm are around £285/kW or 1.6% of total levelised cost of energy (LCOE) and around 12% of the total capital cost based on ORE Catapult’s internal cost model (Table 1). In particular, a breakdown of decommissioning cost by main processes for a 400MW windfarm show 40% of the overall decommissioning cost allocated to offshore preparation, 35% to foundation removal, 19% to vessel mob/demobilisation and 6% to disassembly.⁵

Table 1 Cost of UK offshore wind farm (400MW) decommissioning (installed in monopile foundations and excluding weather downtime)

Component	DECEX (£/kW)	Vessel type	Time (hours/turbine)
Turbine	86	Large jack-up	36
Foundation	130	Large jack-up/feeder barge	24
Array cable	69	Cable-laying vessel	72
Total	285	#	132

Although the decommissioning guidelines suggest that the seabed should be restored to its original condition, the practice of “rigs-to-reefs”, which has been commonly used for US oil rigs in the past

decade, could be considered an alternative strategy under certain circumstances. In this scenario, oil rigs are left in the seabed after cutting the topside and are converted to artificial reefs. It is known that offshore wind structures attract marine life communities so removing their foundations after 25 years of operation can disrupt the ecosystems that have developed over the years. A report published by the Ecological Society of America concluded that “complete removal of a platform resulted in 95% or more reduction in the average fish biomass and annual somatic production at the site, while partial removal resulted in far smaller losses, averaging 10% or less”. In addition to protecting the marine ecosystem, an offshore wind developer can benefit from not incurring the costly and complex removal of substructures. Further discussion between the UK Government and other relevant stakeholders about site restoration, including such aspects as fisheries, safety, security and conservation, is needed to define the best practices from an economic and an environmental point of view.

Repowering

Repowering is the process of replacing the old generating assets with next generation low cost-high output technology, thus providing a “second life” to offshore wind farms and reducing the capital costs of a new project. It usually refers to full repowering, meaning the replacement of turbines, foundations and cabling within the wind farm while keeping the majority of the electrical system in place (export cables and substations). Foundations can last over 100 years for gravity bases depending upon the type and their loads. On the electrical side, array and export cables (transmission cables) could last for more than 40 years, and the transformers for 35.⁶ On average, repowered onshore wind projects have 31% fewer turbines and 1.8 times higher capacity.⁷ We may expect to see a similar trend with offshore wind repowering, but this will depend, among other things, on the rating of state-of-the-art turbines at the time of repowering compared to that of an original construction as well as the potential to increase the export capacity of transmission assets.

In some cases, partial repowering (refurbishment) is more appropriate and includes the installation of components rather than assets (depending on the case) such as rotors, blades, gearboxes, drivetrains, power electronics and/or towers to increase energy output while keeping foundations and cables in situ. This decision depends on factors such as site characteristics, the size of the project, the regulations applicable, the power price and operating costs, the extent of reusable infrastructures, and the expected profitability of the repowered project compared to the actual market.⁸ The last leasing round (Round 4) from The Crown Estate saw an extension of leasing terms from up to 50 to 60 years allowing two full project lifecycles, so repowering can already be considered early on in project planning.

Life extension

The current estimated operational life of offshore wind turbines is 25 years and expected to reach 30 years within the next decade. The lifetime of a wind turbine can often be extended past its design life by conducting minor and low-cost repairs. Lifetime extension or continuous operation should not be confused with repowering where major components are upgraded as in this case existing assets are fixed with small repairs. The usual process is for the wind turbine to pass a fatigue assessment before any corrective maintenance takes place. Foundations are a complex and expensive part to be replaced which means that fatigue loads, seabed conditions and operational asset integrity, defined in the early stage of windfarm development, play a key role in the life extension decision. Operational costs also increase as an asset ages, so the developer should assess regularly the viability of this

strategy through inspections, operational data, or both. A global survey on the development of levelised cost of energy (LCOE) showed that an offshore wind farm's life can be extended by up to 50% based on an average operational lifetime of 20.3 years.⁹

END-OF-LIFE SCENARIOS

Cost comparison

To make a like-for-like cost comparison of end of life strategies a few years before the end of a wind farm's life, the net present value (NPV) of expected future cash flows resulting from different end-of-life decisions was estimated for a number of scenarios. This analysis considers a representative UK offshore wind farm comprised of 35 wind turbines installed in monopiles in 25m water depth and 60km distance from shore using HVAC export cables. The wind farm is supposed to reach the end of its 25-year lifetime in 2040. 6MW rated wind turbines were used for the base case scenario. In this analysis, the developer had to choose between five different end-of-life options (scenarios).

- Full removal: removal of foundations, turbines and array cables.
- Partial removal: removal of turbines and burial of array cables. Foundations stay in place.
- Full repowering: the site is installed with new (larger) turbines (10MW), likely meaning decommissioning of existing turbines, foundations and array cables, with the possibility to extend the life of, and add further capacity to, existing electrical transmission assets (i.e. building on additional substations and export cables to allow export of 350MW (35 x 10MW turbines vs 210MW (35 x 6MW turbines).
- Partial repowering: replacing only existing turbines with new and larger ones (10MW).
- Life extension: Conducting Lifetime Technical Evaluation (LTE) to check if any major defects exist which can prevent life extension. In many instances, the bolts attaching the rotor blades to the hub need replacing, as they tend to reach their design limits more quickly. Replacing these bolts is a relatively straightforward procedure that requires only a limited period of downtime. It was assumed that in this scenario the developers will face only the cost of LTE and any extra costs of minor repairs.

The results from the five scenarios were as follows:

- Decommissioning scenarios resulted in negative NPV of £22 - £55 million as these strategies do not generate any future revenue.
- Partial repowering showed the highest NPV (£221 million) considering that the windfarm can double its lifetime extending this for another 25 years. If larger turbines can be installed on the existing foundations and use existing array cabling, then the developer can maximise its electricity production with minimal extra cost.
- Life extension is the second most profitable strategy (£14.8 million) having the lowest extra cost among all scenarios but also preserving the same annual electricity production for a

limited additional period of 10 years. If the windfarm could extend its life for a further five years (i.e. 15 years in total), then the NPV would reach £218 million.

- Full repowering can create positive cashflows similar to partial repowering, but the cost of replacing foundations and cables reduces the return the developer can expect (£105 million).

The assumption in the partial repowering case is that 10MW turbines can be installed on foundations and use array cabling put in place for 6MW turbines, but this is likely to be optimistic, and so the resulting NPV of £221 million should be seen as the absolute upper end of estimates. However, it is crucial to note that the full repowering and life extension scenarios result in NPV greater than £100 million, demonstrating the economic viability as well as environmental imperative.

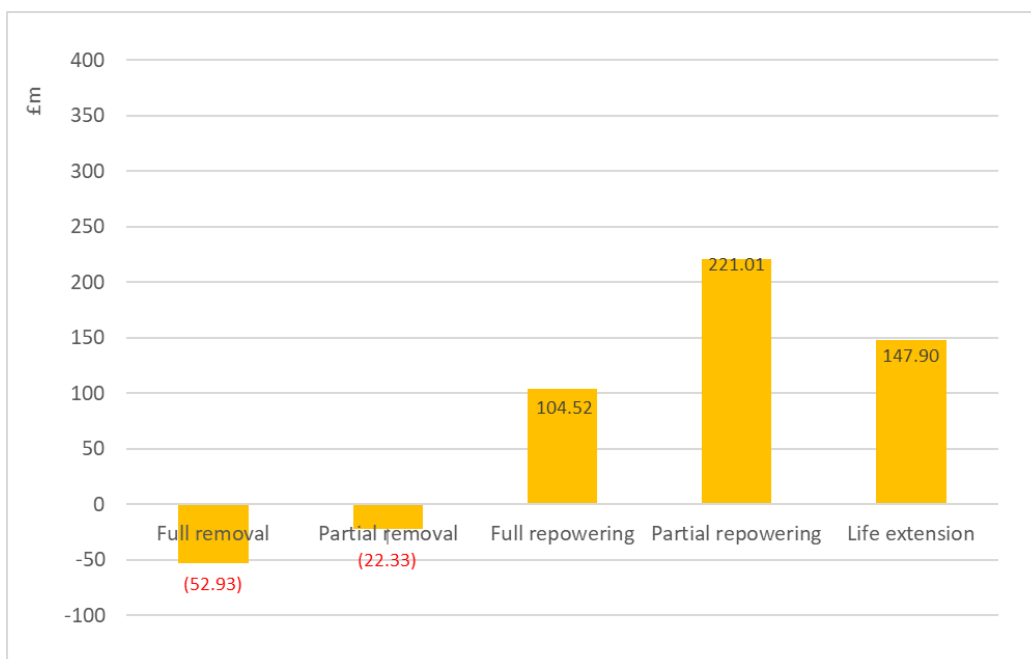


Figure 2 NPV comparison of end-of-life scenarios

Vessels carbon footprint

As well as the financial returns, the environmental impact of each strategy should sway the choice of scenario. For each of the scenarios, the marginal carbon footprint from the vessels used in carrying out the end-of-life strategies was estimated. This only refers to the vessels hired for decommissioning and/or installation of new components and not any further carbon emissions from transportation of waste onshore. Figure 3 shows that life extension has the lowest emissions, as only inspection vessels and crew transfer vessels (CTVs) are required to conduct minor repairs. As expected, full repowering requires installation vessels to remove old assets and install new ones. It should be noted that decommissioning will eventually need to take place at the end of repowering and life extension scenarios but this is not included in the comparison above as this refers to decisions at the end of a second life further in the future, and the current data and projections of cost and emissions may be unrealistic.

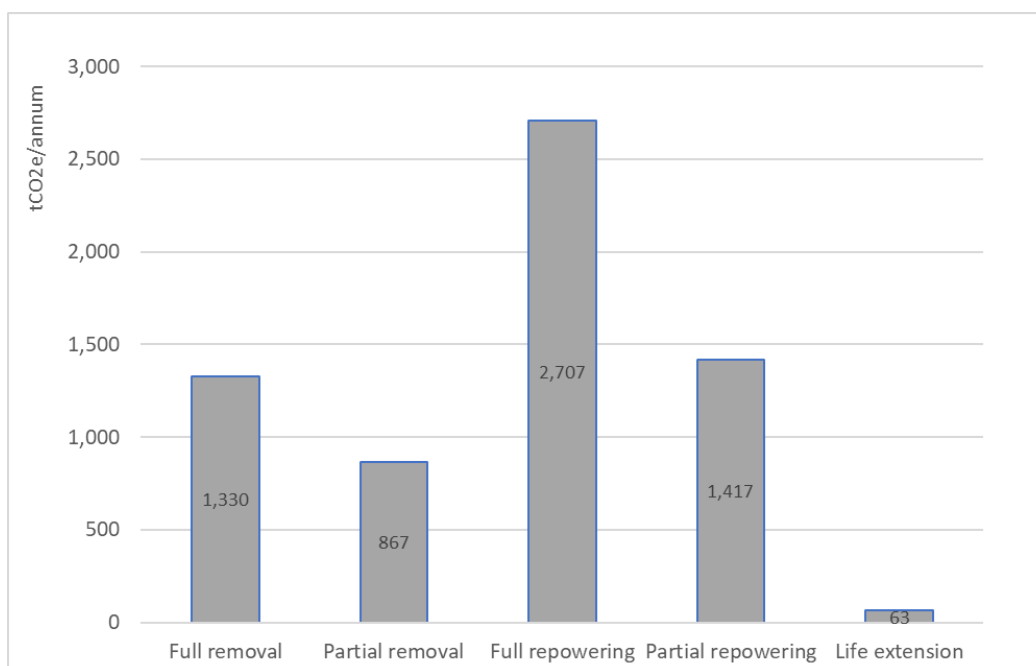


Figure 3 Comparison of marginal vessel carbon footprints for end-of-life scenarios at 25th year (excluding the first installation)

If the emissions from final decommissioning after repowering and life extension are taken into account, and are conservatively assumed to be at the same level as for decommissioning the original projects, a like-for-like comparison of decommissioning vessel emissions would be as shown in Table 2.

Table 2 Estimated decommissioning vessel emissions per operating year

Scenario	Full removal	Partial removal	Full repowering	Partial repowering	Life extension
End of Life 1 (emissions from activities - tCO ₂ e)	33,239	21,668	67,679	35,434	1,575
End of life 2 (decommissioning emissions - tCO ₂ e)	-	-	34,441	33,494	33,239
Total end of life (1+2) emissions (tCO₂e)	33,239	21,668	102,120	68,928	34,814
Total windfarm lifetime (years)	25	25	50	50	35
Annualised end of life emissions (tCO₂e/annum)	1,330	867	2,042	1,379	995

Carbon abatement

Any manufacturing process, even green manufacturing, produces some carbon emissions through the lifecycle of the final product, but it should be borne in mind that the operation of a wind turbine may offset that initial carbon emission or even create a negative carbon emission balance. Electricity produced a few decades ago from conventional fuels in coal plants was a big carbon emitter. Natural gas is currently the most widespread source of electricity generation in the UK which, although less harmful for the environment compared to coal, still has a high carbon footprint.

Considering fuel input for each kWh produced, natural gas emissions are estimated at 0.185 kgCO₂e/kWh compared to 0.277 kgCO₂e/kWh for coal used for electricity generation.¹⁰ Wind turbines produce clean electricity using only wind power which is a variable resource depending upon location, season and weather conditions, therefore the “fuel-related” emissions for wind are zero.

Considering the full life cycle, taking into account emissions embodied in manufacture, installation and operations and maintenance (O&M), current estimates for offshore wind are around 0.011 kgCO₂e/kWh.¹¹ This is less than 2.5% of the estimated life cycle emissions from a natural gas plant of 0.450 kgCO₂e/kWh.¹² Extending the life of existing windfarms either through repowering or delay of decommissioning and recycling of materials can lead to even higher levels of clean electricity generation from the same windfarm with a lower amount of primary resources spent per kWh generated.

Figure 4 illustrates the MT of CO₂e saved from a windfarm’s electricity generation during its lifetime compared to the same kWh produced by a natural gas plant. The base case refers to a 6MW-turbine offshore windfarm (210MW) operating for 25 years, which saves 3.6 MtCO₂e over the 25-year life. Windfarm life extension means more clean electricity and carbon saving using the same assets, giving a further saving of 1.45 MtCO₂e for these extra 10 years of electricity generation (an additional 0.15 MtCO₂e savings per year). Repowering for 25 years at the end of the initial useful life, by upgrading the existing assets with 10MW rated turbines (350MW), can increase savings compared to the base case of 6.40 MtCO₂e (0.26 MtCO₂e per year).

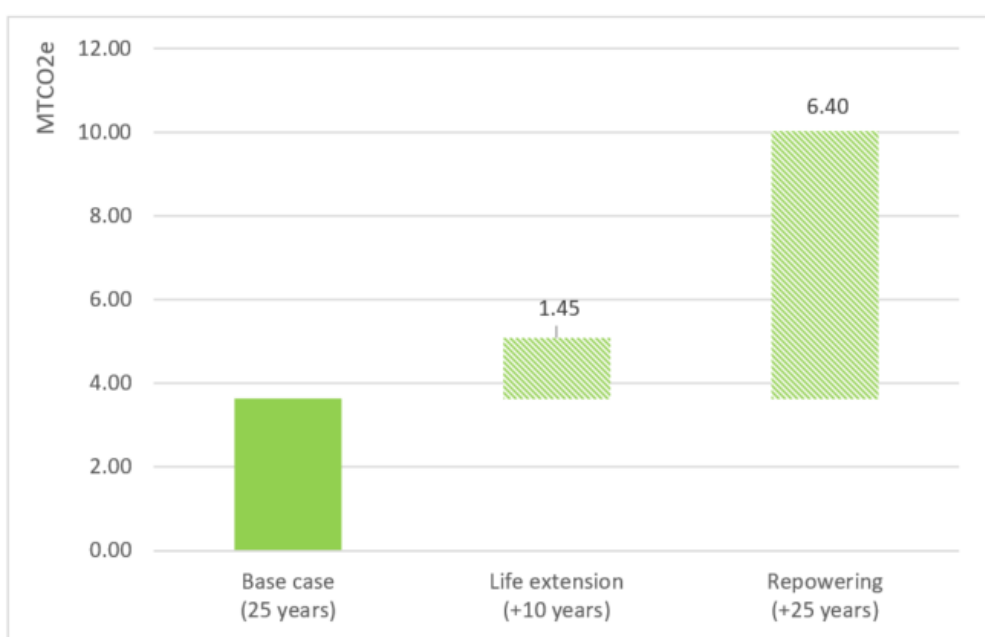


Figure 4 Carbon saving abatement of natural gas due to offshore wind electricity generation

CONCLUSIONS

- About 600 offshore wind turbines should be decommissioned by 2030 with 72% of them based upon monopile foundations.
- Our estimated costs for decommissioning a 400MW offshore wind farm are around £285/kW or 1.6% of total levelised cost of energy (LCOE) and around 12% of the total capital cost.
- There is currently no standard legislation to specify the best practices after operational life end with decisions strongly driven by the physical conditions, theoretically admissible lifetimes of turbines, site conditions, country legislation, logistical difficulties and environmental impact.
- Decommissioning can be delayed so as to postpone turning old fleet turbines and their materials into waste. Life extension and especially repowering are currently considered as alternative strategies to extend the life of valuable assets.
- The analysis showed that partial repowering with a 10MW turbine upgrade in a 210MW offshore wind farm site has the highest NPV of £221 million, extending the wind farm's life for a further 25 years and its electricity generation by 34,575GWh.
- Life extension is the second most economically attractive option with £148 million NPV while having the lowest extra cost among all scenarios but also preserving the same annual electricity production for a further 10 years.
- Compared to partial repowering, the cost of replacing foundations and cables reduces the return the developer can expect from full repowering to £105 million.
- Total and partial decommissioning do not offer any wind farm revenue return to the developer.
- The carbon footprint of vessels hired to conduct full repowering showed the highest emissions (2,707 tCO₂e per annum) of all scenarios and life extension the lowest (63 tCO₂e per annum).
- A carbon abatement of approximately 0.15 MtCO₂e per year can be realised from a 6MW-turbine offshore wind farm (210MW) during its lifetime, compared to the same electricity produced from a natural gas plant. This carbon saving can be increased to 0.26 MtCO₂e per year if this wind farm is repowered for another 25 years with 10MW rated turbines (350MW).

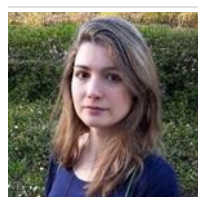
Appendices

RECOMMENDED READING

[Guide to an offshore wind farm](#)

[Circular Economy for the Wind Sector \(CEWS\) - Information Pack](#)

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