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A Review of Life Extension Strategies for Offshore Wind Farms Using Techno-Economic Assessments

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Abstract: The aim of this study is to look into the current information surrounding decommissioning and life extension strategies in the offshore wind sector and critically assess them to make informed decisions upon completion of the initial design life in offshore wind farms. This was done through a two-pronged approach by looking into the technical aspects through comprehensive discussions with industrial specialists in the field and also looking into similar but more mature industries such as the Offshore Oil and Gas sector. For the financial side of the assessment, a financial model was constructed to help portray a possible outcome to extend the life for a current offshore wind farm, using the existing data. By employing a techno-economic approach for critical assessment of life extension strategies, this study demonstrates the advantages and disadvantages of each strategy and looks to inform the offshore wind industry the best course of action for current wind farms, depending on their size and age.

Keywords: decommissioning; life extension; repowering; offshore structures; wind power

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1. Introduction

Wind farms for UK energy generation in offshore sites (as opposed to onshore/land based) have only been commercially viable for 30 years or so and the scale of the farms and the size of turbines have dramatically increased in the last 15 to 20 years. As the mid-2020s approach, first-generation farms should be entering a decommissioning phase as they reach their originally expected end of life. In its simplest form, decommissioning is the reverse of installation. Although the onshore wind industry gives a framework for turbine decommissioning costs, one other factor that crucially impacts the offshore sector is environmental regulations. When first-generation offshore wind farms were installed, decommissioning costs were inaccurately estimated due to limited data points available at that time. Not only were the financial estimations imprecise but over the years the environmental requirements have changed and have largely become more demanding. This will further impact the financial model for decommissioning.

It should be noted that decommissioning a turbine has to be done under general provisions of 'the polluter pays' which are strict environmental standards set out by both the UK and the EU. They require that the site is left as it was found and there is limited to no long-term impact on the environment. The first commercial size offshore wind farm to be decommissioned was the Swedish site, Yttre Stengrud, in November 2015. The farm consisted of 5 × 2 MW turbines and was initially installed in 2001; therefore, the farm operated for many years less than the currently expected life of 20–25 years. By 2014, only one of the five turbines were still operating, and the cost of repair was greater than the cost of removal. This resulted in the total decommissioning of the site. Current owners/operators are constantly looking to improve efficiency and lower costs while looking at installation and energy generation. As the industry has changed rapidly during this period, there are many different designs and sizes of wind turbines across the sites and it has learnt from earlier mistakes and failures. This means that Yttre Stengrud is likely to be an outlier in terms of total offshore farm life.

Decommissioning should be assessed on a site-by-site basis, taking account of many separate factors such as the site characteristics and the age, the type of structures involved, the equipment used, the market conditions and contractual terms for take-off supplies. This means that there will be substantial time, effort and funding involved in just assessing the process and costs of decommissioning the farm at each 'decision node'. However, in the 2020s and early 2030s, most of the farms that will be nearing the end of life will be monopile foundations in shallow waters (less than 30 m in most cases) which allows for greater homogeneity in the analysis and will be much easier to analyse than the farms currently being installed. This will allow for a streamlining of the overall assessment for decommissioning and lowering of the costs of inspection.

Repowering for onshore wind farms will be cost-effective by simply replacing nacelles and blades at the end of an expected nearly 20-year life, at a cost of only 20–30% of the cost of a new turbine [1]. This works well for the onshore industry as reusing the same wind farm area and layout should reduce possible social and planning issues. There is also the electrical infrastructure that allows for the large change in the generation amount. For offshore wind, it is less straightforward, there being a physical limit that repowering can give. An offshore turbine from 2020 will be dramatically different from the first generation farms installed in the 1990s. While engineering sets a 20+ year life for nacelles and blades, other aspects have potentially greater longevity, from hardware such as towers, foundations, cables and substations to intangibles such as permits and leases.

The offshore oil and gas industry is an informative comparator for offshore wind because it is much more mature, having operated in the North Sea since the 1960s. Most of the structures used by the oil and gas industry use similar materials and corrosion prevention methods to those in the offshore wind farms. Therefore, a significant amount of the development of the sector has replicated what has happened in the oil and gas industry's longer lifetime. Having said that, there are fundamental differences in the size, damage tolerance and loading condition of the offshore wind turbines compared to oil and gas pipelines. Therefore, there is an essential need to develop knowledge-based approaches which are specific to offshore wind turbines. The assessment approaches which have been previously employed by other researchers on a range of engineering structures in the energy sector are the reliability-based analysis [2], economic [3], life-cycle [4], techno-economic [5], etc. Among these approaches, the techno-economic method is the one which is of great interest to offshore wind industry [6,7] due to its multi-assessment criteria to consider post-design life scenarios for currently installed offshore wind turbines. Following a simplistic approach which is easy to understand by a broader range of engineers and scientists working on the design and assessment of offshore wind turbines, this study aims to provide an overview of the current knowledge on issues around the end of the expected life and set out the advantages and disadvantages of each of the possible scenarios. The results from this study are expected to have a significant contribution to knowledge by considering both economic and technical considerations in the assessment of suitability of post-design life options available to offshore wind owners and operators, and also opens new avenues for further research investigations in the future.

2. A Review of Current Technical Considerations in Post-Design Life Decisions

2.1. Offshore Oil and Gas Industry

Offshore oil and gas are the most well-established industry in which the structures operate in the marine environment, therefore the knowledge and experience developed in this energy sector over the past few decades can provide useful insights in the decision-making process for offshore wind turbines. Decommissioning is an increasing activity in the North Sea oil and gas industry. It was reported in 2019 by oil and gas UK that over $19 billion would be spent in the sector over the next decade, leading up to 2030. Decommissioning accounted for 45% of the prediction. However, the industry is changing its views of decommissioning as it transitions to a world where oil takes a smaller role in the global energy production. Here are a couple of examples: Equinor and Rockrose.

Equinor's Statfjord A platform has been commissioned to produce oil until 2027. This means that it will almost reach its 50th year of active operation. The field is estimated to have generated income of $180 bn throughout its life, but this has not stopped the drilling of 100 new wells being planned. This sort of super extended life is becoming common throughout the industry.

It is not just oil giants who are looking at life extension in a positive way, so are smaller companies in the North Sea. Rockrose Energy, which is a small UK-based independent oil and gas company, announced that there would be a 5-year extension to its Ross and Blake fields based within the North Sea, with the new expected end of life to be within 2029. Rockrose plans to invest $250 m into the farms, with an aim to fund new drilling work that will see two additional infill wells constructed [8]. Only the future will we be able to tell if Rockrose's project will prove financially viable in the long term when oil is on the decline. Furthermore, within an industry that seems committed to decommissioning, companies such as Rockrose can take a more proactive, expansionist approach to their assets with current success.

The consideration in post-design life scenarios could easily be translated to the offshore wind due to the similar environmental conditions that the structures from both energy sectors operate in. While most of the currently installed offshore wind farms around the world have not reached 15 years of operation yet, in engineering structures which are nearing obsolescence there is still the ambition to renovate 50-year-old hardware.

Currently, around 1/3 of all in use platforms within the North Sea are older than 25 years. They have been able to maintain this amount due to the Ageing and Life Extension Network, which is a group of 90 members, operators, ICPs, designers, contractors, plus HSE. The purpose of the group is to share good methods and practices concerning ageing, identify key elements in ageing processes and to develop guidance [9].

Crucial as these platforms have got older has been a greater requirement for health and safety on the platforms. This must mean that despite the physical structures getting older and needing repairs, year on year there are fewer injuries on offshore oil and gas platforms as shown in Figure 1.

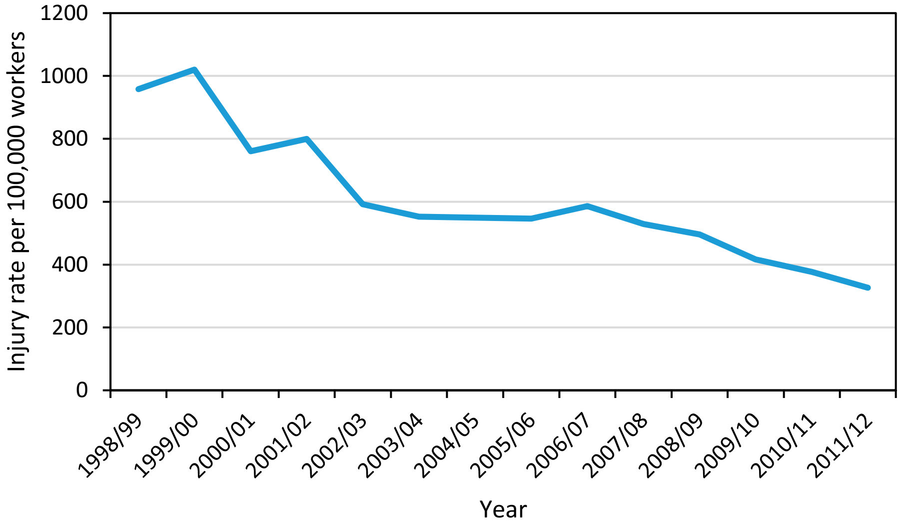

Figure 1. Oil and gas offshore injuries over 3 days from 1998–2012 [9].

The experience of relatively long lifespans in offshore oil and gas structures implies that there is a great potential for offshore wind turbines to also operate beyond 20–25 years that they are initially designed for [10]. This is particularly important considering that the design rules specified in international standards for offshore wind turbines [11], which have been originally taken from offshore oil and gas industry, are overly conservative.

Therefore, the operational life of these renewable energy marine structures can be safely extended by employing appropriate technical considerations on the life extension and repowering evaluations. Furthermore, the lesson learnt from offshore oil and gas industry is that the health and safety aspects must be carefully considered alongside technical aspects when the life extension scenarios are considered for offshore wind structures. The offshore wind industry is increasingly implementing further health and safety measures in order to reduce the number of fatalities and injuries in the offshore wind sector. An important initiative, which has been developed in collaboration with the largest offshore wind operators in the world, is G+ which has set an important target of improving health and safety in the offshore wind industry [12].

2.2. Environmental Impact of Decommissioning

One of the areas which is crucial to consider in the decommissioning process as a post-design life scenario is the impact on the marine environment [13].

As far as the environmental impact is concerned, there are two major criteria that need to be investigated and considered:

- First, the question of a total or partial removal. It is a requirement that offshore sites should be vacated and left as they were before the turbines were installed [14]. However, there have been discussions around the positive environmental benefits of only partially removing an offshore wind farm. Regarding the transmission system, the buried subsea cables are usually around 1 to 2 m deep [15]. The process of removal through the use of seabed excavation and extraction for many miles would cause significant disruption to the marine environment, not to mention the sizable costs. A significant research in the [16] details of the 'renewables-to-reefs' program in which the positives of partial removal for both the environment and economy are explored. It is worth noting that an offshore structure in use surrounded by wildlife will grow the used to it and an ecosystem will grow, and underwater 'abandoned' structures can become habitats for marine wildlife [17–19]. This is a clear example which highlights the importance of considering the environmental impact of decommissioning the decision-making process.
- Secondly, decommissioning should be carried out in a sustainable manner through the use of recycling and reusing methods, and must contribute to the circular economy. Wind turbines are mainly made from steel, so as much as 95% of their mass can be recycled [20]. The difficulty comes when trying to recycle the last 5% which is mainly the electronics, lubricants and polymers. The blades are made of polymers and therefore are currently completely non-recyclable [21]. Blades are certainly the biggest challenge for material recycling and transport logistics [22]. Finally, the growing size of wind turbines is going to be a drawback for recyclability. Indeed, the raw materials required for two small wind turbines are less than those for an equivalent capacity single turbine [20]. As a result, the current trend for larger offshore wind turbines means there will have to be better use of raw/re-used materials for the installation in order for the whole life cycle of the turbine to be suitably sustainable when accounting for the whole decommissioning process.

Most parts of first-generation wind turbines are easily recycled due to their mainly steel construction, with the turbines being between 85–90% recyclable [23]. As the industry develops, there is a requirement to push the recyclability closer to 100% to help join the future circular economy being set out by the leading countries. Currently, the industry is showing great steps towards this future, with the foundation, tower, components of the gearbox and generator being recycled. The main difficulty comes to the turbines since they are constructed of a composite of materials to make them as light but long as possible. A typical 2.0 MW turbine has three 50 m long blades containing around 20 t of fibre reinforced polymer (FRP) composites [23]. As of February 2020, 2.5 million tonnes of composite materials are used in the wind sector all over the world. The current estimation is that by 2050, 39.8 million tonnes of material from the global wind industry will need to be disposed of [23].

Wind turbine blades are mainly made of glass fibres, resins and foams. This makes them hard to recycle due to them not being biodegradable. There are a few companies such as Re-Wind [23] that are looking into repurposing wind turbine blades, but so far many of the ideas are new and costly to implement [24]. Currently, the main system used to recycle composite waste is through cement co-processing. This is, however, a poor method, the wind sector uses the method much less than that of the building, transport and electronic sectors [20].

Alternative technologies development in areas such as solvolysis and pyrolysis will help give the wind industry additional solutions for turbine blades when they reach their end-of-life and will assist in the delivery zero-waste turbines [25]. With current projections, around 14,000 wind turbine blades will be decommissioned in Europe by 2023 [24].

In summary, one of the areas which must be included in the technical assessment of post-design life strategies is consideration of the potential impacts on the surrounding environment. This can include the marine wildlife as well the as requirement of moving towards a 100% circular economy. For the latter, as far as the offshore wind turbines are concerned, there is an essential need to develop efficient recycling methods for the composite materials employed in the fabrication of offshore wind turbine blades.

2.3. Corrosion of Offshore Wind Support Structure

Offshore wind turbines are built in an environment that consists of aggressive alkali seawater, temperature cycles, tidal fluctuations and variable cyclic load due to wave and wind impact. Therefore, in the structure, there is a high likelihood of both fatigue and corrosion damage to the turbines. This means there is a requirement for continual checks of the structures while in use and also the employment of corrosion protection methods. Untimely failures of offshore wind turbines occur even with the application of corrosion protection methods and performing regular inspections and maintenance. Corrosion mechanism and degradation rates are greatly affected by the composition and physical characteristics of the corrosive medium (seawater).

Natural seawater is a complex system consisting of a unique chemical combination of inorganic and organic compounds and countless types of living organisms. Seawater is slightly alkaline with pH varying from 7.8 to 8.3, while surface waters are usually more alkaline with a pH greater than 8. The chemical and biological profiles of open seas and coastal water can significantly differ. Coastal waters are often polluted due to human activities and become a more aggressive environment for structures. Industrial, domestic and farming waste and marine transport pollution introduce heavy metal ions, nutrients, organic matter etc. in the marine habitat. Consequently, metal degradation can occur through different corrosion mechanisms [26].

The detailed analysis of the level of corrosion damage at different parts of the offshore wind turbine is presented in Figure 2 and Table 1.

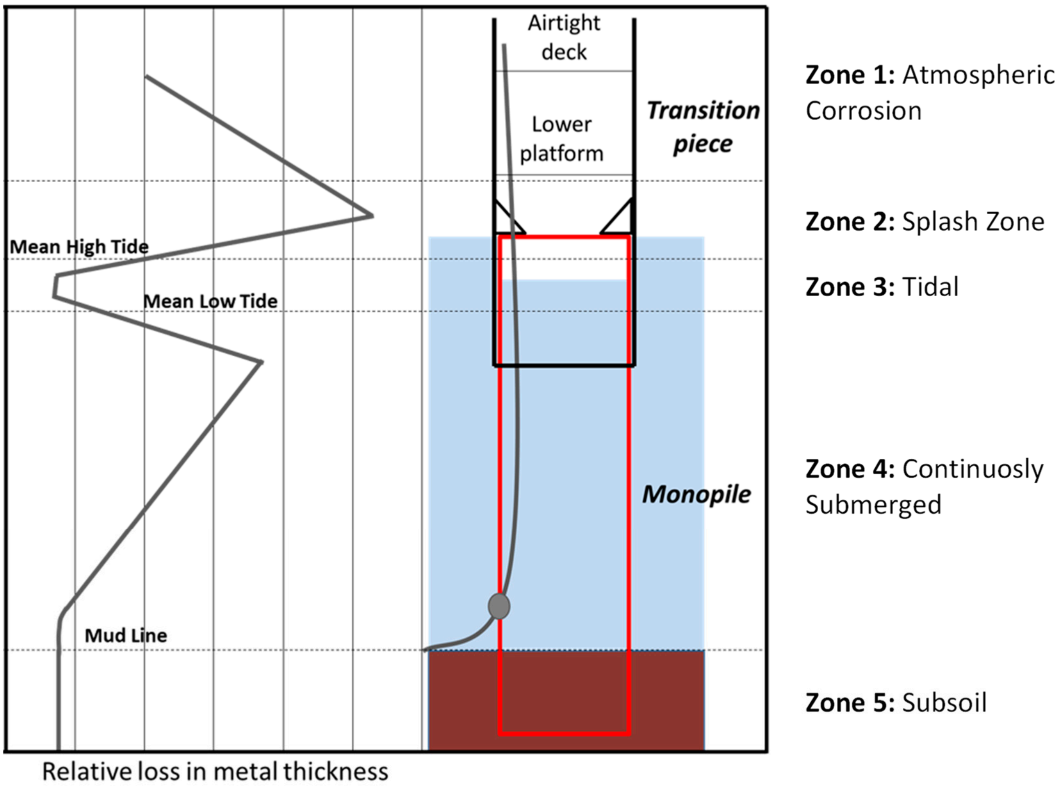

Figure 2. Suggested relative loss of metal thickness of unprotected steel on offshore wind turbine structure in seawater [27].

Table 1. Wind turbine corrosion zone explanation in relation to Figure 2.

Zone 1 **Atmospheric corrosion**	The atmospheric zone has the least amount of corrosion due to the only contact with seawater coming in the form of droplets from seawater spray, the protection method is a coating on the outside of the turbine. Corrosion rates 0.050–0.075 mm/year [28].
Zone 2 **Splash zone**	In the splash zone, the corrosion effects are amplified compared to that of the atmospheric zone. The waves continually splashing on the surface causes there to be a continual wetting and then removal of water to allow for the movement of ions. This allows for deep pits to form in this area if left unprotected. Heavier external protection would be used in the area but internally there is usually no protection and corrosion is allowed due to the less of a wave effect internally. Corrosion rates 0.20–0.40 mm/year [28].
Zone 3 **Tidal zone**	The tidal zone has a mix between both Splash and Submerged zone. The wetting and drying effect aren't as aggressive here with it only happening as the tide rises and falls. This causes there to be an overall lower rate of corrosion but there can be more aggressive local corrosion spots. The cathodic protection is designed to help this area when in high tide. Corrosion rates 0.05–0.25 mm/year [28] with localised corrosion rates up to 0.50 mm/year [29].
Zone 4 **Submerged zone**	When submerged, the main corrosion protection method is the use of cathodic protection. This has to be changed regularly and maintained. This is often used internally but might not be checked and changed as regularly, with some corrosion allowance. Pits in immersed zones are usually broad and shallow with growth rates 0.20–0.30 mm/year [30]. Uniform corrosion rates 0.10–0.20 mm/year [28].
Zone 5 **Buried zone**	When looking at the structure underneath the seabed it can be assumed that there is low uniform corrosion but there can be pockets of localised corrosion around the mudline. While it is not yet decided in the industry what is the best course of protection for buried areas, cathodic protection is most likely the best though [31]. Corrosion rates of 0.06–0.10 mm/year are expected [28], however [29] reports show possible pitting rates up to 0.25 mm/year.

A commonly used standard in offshore wind, DNVGL-RP-0416, states that it should be expected that the minimum uniform corrosion rate for a submersible part is 0.10 mm/year for internal surfaces and 0.30 mm/year for external while looking at turbines in the North Sea [32]. More details about the formation and evolution of corrosion pits can be found in Figure 3.

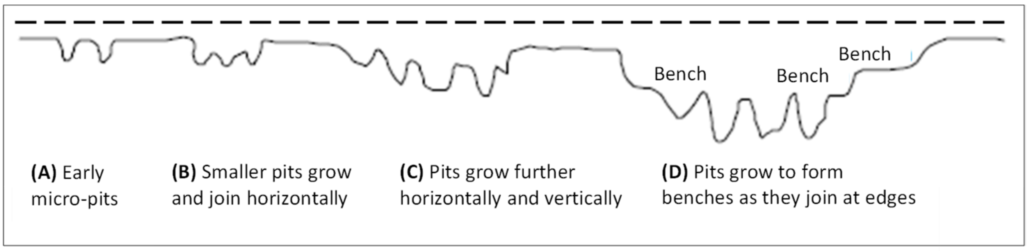

Figure 3. Proposed model of pitting growth [33].

These mm/years' number should be noted when looking at possible life extension situations because it can easily be calculated as the actual loss of material over the 20-year period compared to the supposed minimum loss of 2 mm for internal surfaces and 6 mm for external surfaces. Moreover, it is worth noting that once the corrosion pits reach a critical size, short cracks will be formed in the submersible structure which will subsequently lead to long cracks under fatigue loading conditions. Therefore, the corrosion-fatigue behaviour of the steel structures must be carefully studied and accounted for in structural integrity assessment procedures.

In current thinking, it is well accepted that corrosion overall is a detrimental occurrence in structural applications, and therefore in regulations and standards surround offshore wind there is a requirement to counteract corrosion. This would be a large stumbling block if life extension was being looked at, because as seen in Figure 3 corrosion builds up over time from pits with this then slowly removing a top layer of material. It should be stated that there is little to no research into 20+ years in terms of corrosion due to the time length. The main issue with understanding and modelling corrosion is that it is a time-consuming process. Therefore, one of the technical considerations in the post-design life decision-making process is to predict the level of corrosion data both in the form of uniform corrosion (i.e., material loss) and crack initiation and growth from corrosion pits. In order to achieve this goal, accelerated corrosion-fatigue testing mechanisms need to be developed in future research to study the long-term effects of corrosion in conjunction with fatigue damage on the global response of submersible steel structures in offshore wind turbines.

3. End of Design Life Scenarios for Offshore Wind Turbines

3.1. Overview of the Decommissioning Process

The expected lifetime of an offshore wind farm is 20 to 25 years. During initial design, considerations in relation to decommissioning are thought of, with a view to keeping them as low as possible. The overall project plan and formal approval dossier will include a proposal for decommissioning.

When decommissioning there are many things to consider; a few major ones are the foundation type, the specialised equipment and vessels available, the distance to ports, the water depth and the weather conditions.

The most important thing is to move every structure in the largest form possible and then deconstruct while on land. This will not only reduce the time but in fact is much safer and lowers the risk of the operation by removing factors such as high winds and stormy seas.

This can be divided into three different phases [34]:

- Project management and planning;

- The removal of the structures themselves;
- Post decommissioning processes such as the destination of the removed elements or the monitoring of the site's recovery.

Repowering can also be considered a type of decommissioning-cum-recommissioning with the installation of more powerful generation machines on existing structures or foundations while preserving the majority of the electrical systems (cables and substations), which substantially reduces the capital costs of the new project.

The lifetime of foundations will depend on the type and the loads they receive and should last at least 100 years for gravity bases. Transmission cables can last more than 40 years, and the transformers 35 years [34].

Taking an early windfarm, like Nysted, commissioned in 2003 with expected lives for the foundations and transmission cables of at least 50 years, this is now faced with two options:

- Partial repowering which within this study is labelled as 'Life Extension'. This is the process of upgrading minor components such as rotors, blades, gearboxes, drivetrains, power electronics and/or towers.
- Full repowering which within this study is labelled as 'Repowering'. Replacing old turbines with much larger ones requiring larger changes to the infrastructure found at the site. However, some parts are to be reused.

The actual decisions taken will have to take account of the specific physical features of the site, the regulatory situation, the changed financial landscape for energy subsidies and the view of energy prices. All these 'known' elements are set against the unknown aspects of real decommissioning and the value of decommissioned structures etc.

3.2. Decommissioning

3.2.1. Removal

Each structure in a wind farm will be removed in its own way with specific equipment.

Turbines

As mentioned before, wind turbines are all different, each installation is slightly different, consequently so is the removal. A system of removal would have been suggested when each farm was installed. However, developments in the last 20 years might bring some innovation to the process; so, a review should be undertaken as part of the initial decommissioning survey. Traditionally, the whole wind turbine would be removed and then broken up into parts onshore.

Nowadays, some turbines might need some disassembly at sea, especially the larger and heavier ones. While it costs more to break up at sea, the reduction in size of the product to be transported would mean cost savings overall.

Wherever the disassembly takes place, care must be taken with recovery and disposal of the internal liquids in the turbine—gear and motor oils—so this might also be done before extended sea journeys.

As the turbines are being lifted the foundations are prepared for removal.

Transition Piece

The transition piece connects the base of the tower to the foundation, usually with a bolted flange connection or grouted connection. It contains access ladders and platforms and will weigh as much as 300 t [34].

This will either be removed with the turbine tower or with the foundations; in the latter option the total mass being lifted will be substantial—over 1000 t in some cases—which means highly specialised lifting apparatus and extreme safety measures.

Foundations

Foundations ordinarily represent the greatest mass in a wind turbine installation and there are two methods of repair after the turbine's removal: complete removal or just removal to a distance below the seabed/mudline. In both cases all the fabrications on the concrete will be removed—J tubes, access ladders etc. After total removal, an element of landfilling will be needed to fill the inevitable hole. While partial removal will not require this expense, the costs of cutting the foundations would typically be quite high.

Partial removal is gaining acceptance over the earlier code of 'left as found'. This reflects that after 20+ years a new ecosystem will have developed on the seabed around the foundations and disturbing/removing this is ecologically and environmentally unsound.

3.2.2. Costs

Current estimations for the cost of decommissioning an offshore wind farm is 2–3% of the total capital cost [24]. Most developers will accrue this amount during the life of the wind farm to pay for its end of life. An accrual starting at the mid-life point is in reality the chosen method as the early years will suffer snagging and post-commissioning costs; so, once these have settled down, the end-of-life issues can be planned for [35].

A plan for decommissioning has to be available at all times due to the requirement that a turbine might need to be removed earlier than expected and being unprepared in such a large operation would be very un-cost effective. The specialist vessel is a vital factor in the process, as it contributes a sizeable amount of the cost. A breakdown of the decommissioning cost for the fixed bottom offshore wind turbines can be found in Figure 4.

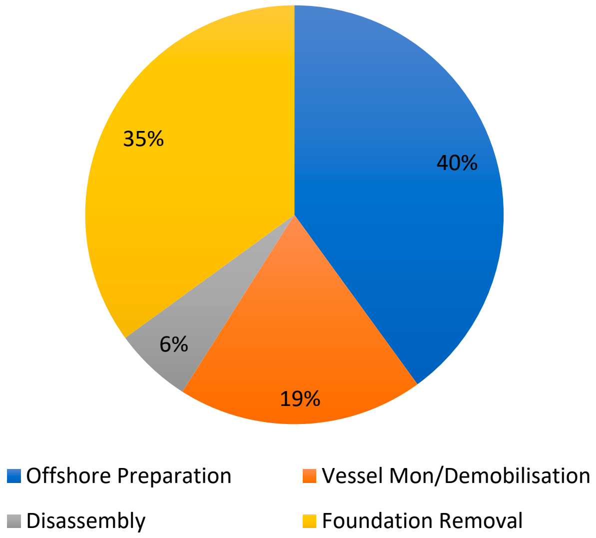

Figure 4. Decommissioning costs breakdown for bottom fixed offshore wind turbines [34].

The removal of the foundations is around half the total cost, as mentioned above. The major element is the disassembly tasks, as these are many time-consuming activities. Publicly available reports rarely mention decommissioning costs or they refer to them as confidential. Table 2 shows a wide range from the limited information once available in the public domain and has been collaborated within [34].

Table 2. Summary table of the decommissioning [34].

Wind Farm/Specifications	Gunfileet Sands	Thanet	Lincs	Ormonde	Sheringham Shoal	Greater Gabbard	Gwynt Y Mor
Commission Year	2010	2010	2012	2012	2012	2013	2014
Capacity (MW)	172.8	300	270	150	316.8	504	576
Distance (km)	8.5	11.3	8	9.5	17–23	26	13–15
Depth (m)	2–15	20–25	8–18	17–22	15–23	20–32	12–34
Seabed Material	Partially lithified cross-bedded sands	-	Glacial till, cretaceous chalk *	-	Soft clay, chalk	Silty clay, clayey, sandy silts, sand	Granular sediments, sand, glacial till
Turbines (MW)	48 × 3.6 (SWT-3.6-107)	100 × 3 (V90-3)	75 × 3.6 (SWT-3.6-120)	30 × 5 (5M)	88 × 3.6 (SWT-3.6-107)	140 × 3.6 (SWT-3.6-107)	160 × 3.6 (SWT-3.6-107)
Weight (t)	475	396	435	661	475	475	475
Expected Life (years)	20	20 × 2	20 × 2	-	20 × 2	25 × 2	(20–23)
Meteorological Mast and Foundation Type	Monopile	Monopile	Monopile	-	-	Monopile	Jacket
Weight Transition Piece (t)	230	-	290	500	200	300	-
Foundation Type	Steel Monopile: Cut (1 m)	Steel Monopile: Cut (2 m)	Steel Monopile: Cut (1 m)	Steel Jacket: Lifted + Cut (1 m)	Steel Monopile: Cut	Steel Monopile: Cut	Steel Monopile: Cut
Weight (t)	225–423	-	225–320	250	370–500	660	200–700
Foundational Depth into Seabed (m)	27–38	-	15–30	-	23–37	30	-
Offshore Substation	Monopile Cut (1 m)	Jacket lifted + Piles Cut (2 m)	Jacket lifted + Piles Cut (1 m)	Jacket lifted + Piles Cut (1 m)	Monopile Cut	Jacket lifted + Piles Cut (1 m)	Jacket lifted + Piles Cut (1 m)
Weight: Topside,	1315, 414	1460, 820	2250, 970	900, 540	875, -	500, 850	1415, 400–1000
Scour Material Interray Cables	Left in situ Copper 33 kV: Left*b	Copper 33 kV: Left (buried 1–2 m)	Left in situ Copper 33 kV: Left	Copper 33 kV: Left (buried 0.6 m)	Left in situ Copper 36 kV: Left	Left in situ Copper 33 kV: Left (buried 1–1.5 m)	Left in situ Copper 33 kV: Left
Total Length (km), Section (mm^2)	36, 500/150	65, 95/300/400	185/630	27, 150/300/500	3, 400/185	173, 150	148, 185/500
Export Cables	Copper 1 × 132 kV: Left (buried 2 m)	Copper 2 × 132 kV: Left (buried 1–2 m)	Copper 2 × 132 kV: Left (buried 1–3 m)	Copper 1 × 132 kV: Left (buried 2 m)	Copper 2 × 145 kV: Left (buried 1 m)	Copper 4 × 132 kV: Left (buried 1–1.5 m)	Copper 4 × 132 kV: Left (buried 0.5–1 m)
Total Length (km), Section (mm^2)	9.3, 800	51, 1000/630	96, 630	43, 800	44, 630/1000	4 × 45.5, 800	85.2, 500
Decommission Time (days)	100	270	1339	570	1350	260	730
Costs (£/MW)	-	40,000	101,200	-	31,900	-	111,000

Initially, cost prediction was around £40,000/MW [35], but as years have passed this number has increased substantially. DNV GL estimated in a recent study [36] that decommissioning could be between £200,000 and 600,000/MW, so at the top end as much as 60–70% of the installation costs [37,38].

Over time one would expect a decrease in costs as experience and knowledge is expanded. Furthermore, it can be seen that the projected costs are completely different from site to site. Further suggesting that each site will be different to the next and a one price fits all idea is unlikely to work in this case. These large costs could be an overly prudent assessment on the part of the owner/operator or a reflection of the site's complexity.

3.3. Repowering

As mentioned in the introduction, in the onshore wind sector, the idea of the repowering of installed farms is gaining traction. The factors to be looked at when looking into repowering a wind farm are:

- Lifetime extension assessment
- Structural stability of a turbine
- Environmental conditions and required documents
- Physical state of the equipment

3.3.1. Lifetime Extension Assessment

A lifetime extension assessment performed in the final years of the operating permits will determine the condition of the turbine. Some operators are meeting the issue head-on by using the Siemens offering, 'Middle life investment' [39]. This is a program with the aim of extending the life of 20-year farms to 30 years. This works as companies analyse turbines on a continual/regular basis. Many of the modern improvements in the operation and maintenance (O&M) is down to digital detection of possible faults in turbines, lowering the need for physical inspections.

There are two elements to the assessment of suitability for a turbine to have its life extended: experts in analytical and practical evaluation work together during the process. Physical inspections are done both by eye and also with handheld ultrasonic scanners which identify fatigue cracks [40]. Regular inspections will show growth in cracks which can be extrapolated for end-of-life estimations.

The analytical review looks at the electricity generation data for the turbine and compares it to other turbines both in the same farm and others; this produces an efficiency rating. After an analytical evaluation and on-site inspection, an overall report will specify the requirements for lifetime extension. For example, repairs to, or precautionary replacement of, the bolted rotor blade connections are often required. Usually these are the first components to reach their design load limits. Therefore, financial estimates can be made over potential costs involved in a lifetime extension. The results of the assessment provide input to the decision process around the timing of upgrades versus continued operation and possible decommissioning.

3.3.2. Structural Stability of a Turbine

The most important factor within the safety inspection is understanding the structural stability of the wind turbine. When testing for structural stability the load-bearing components are evaluated from foundations to the rotor blades. The safety devices, braking systems and turbine control systems will also be checked. The main aim is to make sure that the turbine has not been affected by environmental load greater than that would have been expected. To do this, the load calculations will be compared with a computer model based on simulation data from testing and environmental operating condition data [41]. Additionally, an on-site inspection of the turbine is performed, as discussed in Section 3.6.

The environmental operating conditions data that are used within the calculations are mainly wind conditions from the specific site, such as the average wind speeds, turbulence intensities and extreme wind events for the operating life, usually 20 years. All turbines have an anemometer on the nacelle which is continually recording this data in relation to the wind for the smoother operation of the turbine. If for some reason there is incomplete data for a certain turbine it can be possible to use other turbines within the same farm's data and extrapolate this. In the case of a wind farm with a variety of different capacity turbines, turbulence is calculated for each turbine as well as for the whole farm layout over the expected lifetime.

3.3.3. Physical State of the Equipment

Before the physical check of an offshore wind turbine through an on-site inspection, many checks will be done on shore using the data available. To help lower the O&M costs, an inspector will spend as little time as possible while having physical presence at the turbine. Technical documentation and reports, as well as weather and performance data, are assessed so that the turbine can be checked for certain flaws and faults [41].

The point of this assessment is to record any known damage or unexpected wear and tear on the turbine. As already discussed, the loadbearing and safety factors would be checked extensively but the whole turbine needs to be checked. Records are kept on the maintenance of each turbine and would be assessed and updated on each inspection. The main targets that are looked out for are possible corrosion, visible cracks and audible issues with the gearbox and generator. Within more modern checks, a computer model will inform the inspector of certain areas that would involve risks and therefore should be checked. As these models improve there will be less of a need to send out as many physical inspections. A premature investigation could also happen on the inspector by randomly spot-checking items, with a hope of finding nothing out of the ordinary.

If any major item is damaged such as the rotor blade, support structure or foundation, a complete shutdown would occur. Usually, this does not happen, and an engineer will arrive on site and complete the work. This is because the damage discovered is relatively minor and caused by corrosion, weathering and fatigue damage.

3.3.4. Analytical Models

All the different data is then brought together to make an analytical model. The operation loads are compared against the original design loads. From this data fatigue loading conditions would also be calculated and estimations on the number of cycles that had been completed. Everything which is load bearing is studied; the tower and foundation, screws and bolts, load-bearing parts of the drive train, the hub, the shaft, the rotor blades, braking systems and the safety functions [41]. The life assessment report will determine a remaining time until design limit is reached, detailing what parts have more longevity than others.

3.4. Life Extension

Extending the life of an offshore wind farm is growing in popularity as many of the structural and logistical issues around repowering are being overcome.

The UK has about 60% of the global offshore wind capacity [42], and its leases have built-in longevity. The permitting process is expensive and laborious, so extending a permit for as long as possible is a major benefit.

The Crown Estate has generally granted leases on the seabed for 40 or 50 years; in recent years this has begun to be longer [1]. So, in the current planning regime, the issue of the leases expiring is being met head on. This is an opportunity to keep projects going, repower or extend their life. However, some round 1 (first-generation) farms do not have this extended lease; however, in light of the current practice it is not seen as likely that an extension would not to be granted.

Most towers due to safety factors have already been engineered for a 40 or 50-year life so they could be used for much longer than the planned 20 to 25-year life span.

Monopile foundations use a lot of steel: for example, 30 m under the water and 30 m into the seabed. It would surely be tempting to replace the business end on top, to maximise what has been invested below the surface.

But attempting to attach a new equipment to older hardware is unlikely to be a simple process. For instance, a 2025 nacelle is likely to be extremely different to a 2005 tower and foundation, so marrying the two together would need extensive research.

Trying to reuse a foundation with a significant difference in the nacelle or turbine could be very difficult as the operating permits for the foundation design and the initial tower would be specific to that installation. These will not be transferrable to different technology.

Therefore, the longevity of foundations and towers does not mean that one could replace the nacelles and blades on top. It will take re-certification from independent engineers as part of a re-commissioning process. Though the theoretical approval would be obtained before the project was 'boots on the ground'.

One issue repowering is likely to resolve is a continual point of failure with all distant offshore wind farms using a single set of export cables. These cables would most likely have been designed for an original farm with not much overhead combined with the aging of the cable, therefore the most sensible option is to keep the old cabling and add new cables to provide a layer of insurance.

3.5. Future Financials

The decision to decommission, repower or life extension would depend on a straightforward commercial assessment in relation to government incentives. The legislative rules and support mechanisms are vital in the development of all alternative and renewable energy—from direct cash subsidies to varying support for the take-off price: cap and collar, extended floor options etc.

No installing/commissioning operator knows what the support/take-off/tariff environment is going to be 20 years after installation. Many of the currently installed first generation turbines are only cost effective due to their feed-in tariff and renewable obligations from a government 15 years ago.

The US has not been able to develop an offshore wind industry at the same rate as Europe, one reason for this is the lack of policy certainty—the political polarisation around renewable energy means that each two-year political cycle can re-set the support environment.

Due to this uncertainty, repowering could be considered risky. There will be aspects, touched on above, which do help: the analytics for actual wind and load bearing on the site mean a future energy yield and maintenance programme can be projected with more certainty. This would be set against the current support environment and the perceived direction of travel.

3.6. Future Operating Models

As in the oil and gas sector where companies like Rockrose have carved a niche from the decommissioning phase of oilfields, it is highly conceivable that niche operators will find an O&M role in the offshore wind sector. This will be supported by new ownership structures which also mimic the oil and gas mature asset sector—majority ownership by financial investors but significant minority interests from nimble O&M companies who will bear the risks repowering and extending the farms.

One of the advantages of repowering is that it delivers a continuous income from the farm—the upgrading of individual elements of the farm will not take out the whole generation system for chunks of time. This means that as more mature farms become financial assets owned by long-term financial investors—pension funds, banks, bond holders and similar—the wholesale scrapping of a performing asset becomes less likely. The scrap value minus decommissioning costs will be weighed against a short-term reduction in revenue, the costs of repowering and the renewed revenue stream for the next 15+ years.

The different dynamic from the oil and gas sector is the role of the original equipment manufacturers (OEM). In the future there will be a point where turbine design will reach a maximum height that is logical for the materials that are being used and has the most optimum design. Once this development cycle has been completed, the capital construction companies will want to cash in on the designs as quickly as possible. The lengthy permitting and initial construction phase accompanying new farms developments will be sliced through if their blades, nacelles and associated equipment are deployed in existing farms as part of repowering investment. Siemens [39] and other equipment manufacturers will invest in large-scale replacement systems/schemes for factory refits and similar.

As the process continues and becomes more established, the parts of mature offshore wind farms will become more recyclable.

There will be a four-way split in interested parties as the decommissioning phase for a farm is approached:

- The existing owners/operators—these will likely have seen the initial projections for a field achieved overall, and avoiding the cost of decommissioning is real bonus, thus they have an incentive to sell on an operating asset.
- Financial investors—may well be invested in the farm already. The steady income generated by a farm with suitably de-risked income streams supported by off-take agreements and government incentives based on floor pricing is very desirable in the current low yield world.
- Capital Equipment OEMs, as noted above so that their hardware is installed, are interested in taking a financial stake in the project.
- Nimble second tier O&M operators, like Rockrose, these will be smaller teams who have analysed the data in a different way and by offering to take ‘difficult’ assets off mainstream generators they create a structure which is financeable and meets all parties’ needs.

4. Financial Model

4.1. Introduction

To give an overview of the possible financial outcomes from either Repowering or Life extension, a basic financial model was created. The model works with annual rests and is designed so that a few different scenarios can be demonstrated, as shown below.

4.2. Inputs

For the model, London Array was used as the example, because it is a large farm, and the financial data are available in the public domain. Table 3 shows the inputs to the model: the London Array values for Rated size of Wind Farm [43], Capacity Factor [44] and Cost per Watt [45]. In Table 3, there are both inputs and calculated values from the inputs. It is generally accepted that there is a discount rate of 4% within the offshore wind industry [46], this is used both in costs and within energy output per year. The annual increase in operational cost was calculated from current wind farms average increase over their current life and comes to 3%. As already discussed, there is a lot of debate about the decommissioning costs, for the model £400,000 per MW has been used—not only is this used in [46], but it is also the middle of the range discussed in Section 3.2.2 above.

Table 3. Inputs for financial model using London Array.

Variable	Symbol/Calculation	Value
System Specifications		
Rated size of Wind Farm (MW)	A	630
Capacity Factor	B	45.300%
Planned Repowered (MW)	C	1100
Degradation rate per year	D	0.0%
Energy Output (Rated) MWh per year	E = B × 365 × 24 × A	2,500,016.4
Associated Costs		
Cost per Watt of System installed (£/W)	F	3
Total installed cost (Million £)	G = F × A × 1,000,000	1890
Insurance (1%) (Million £)	H = 0.01 × G	18.9
Initial Annual Maintenance Cost (3%) (Million £)	I = 0.03 × G	75.6
Annual increase in Maintenance Cost	J	3.00%
Other Annual Operation Cost	K	£-
Other Annual Maintenance Cost	L	£-
Cost Per Watt of Repowering (£/W)	M	1.5
Repowering Cost (Million £)	N = M × C × 1,000,000	1650
New Install Cost (Million £)	O = F × C × 1,000,000	3300
Financing		
Annual discount rate for present-value calculations	P	3.0%
Interest rate for loan	Q	3.0%
Down payment (initial capital)	R	1890
Decommissioning Cost (Million £)	S = A × 400,000	252
New Install Decommissioning Cost (Million £)	T = C × 400,000	440

4.3. Initial Results

Table 4, Figures 5 and 6 show the results from the calculations. Figure 5 shows the annual cost as a function of years in operation for each of the scenarios considered in this study, whereas Figure 6 presents the analysis results in terms of the total (i.e., cumulative) cost for the same scenarios. It is worth noting that in Figure 5, the jumps in the green and red datasets at Year 20 show the "initial" (i.e., capital) cost of repowering and cost of installing a new farm, respectively, whereas the trend in the purple dataset shows the continuous operation of the existing farm (i.e., life extension) for 40 years. The 20-year timeframe demonstrates the farm operating normally and then being decommissioned. The 25, 30 and 40 years that assume various amounts of life extension have been put in place but there has been no major upgrade to the turbines. There are then two different 40-year plans, one looking at repowering the turbines to a higher MW while using existing infrastructure (in this case from 630 MW to 1100 MW) and the other modelling a complete removal and decommissioning of a farm and then a new farm of a higher MW (1100 MW in this case) built on top of the same site.

Table 4. Raw Model Data for London Array.

Loan Term (Years):	20-Year	25-Year	30-Year	40-Year	40-Years (20 Years + 20 Years Reinstalled)	40-Years (20 Years + 20 Years Repowered)
LCOE (£GBP/MWh):	£ 93.27	£89.67	£88.30	£89.07	£71.82	£62.03
Life Extension Cost (20+ years) (£GBP/MWh):	N/A	£38.81	£70.60	£79.80	£59.34	£44.15
Total project cost (current pounds): (Million £)	4379	5220	6181	8536	13,121	11,219
Total project cost (Projected Value): (Million £)	3702	4128	4547	5370	7729	6676
Total project cost With Decommissioning (Projected value): (Million £)	3954	4128	4799	5622	8169	6676

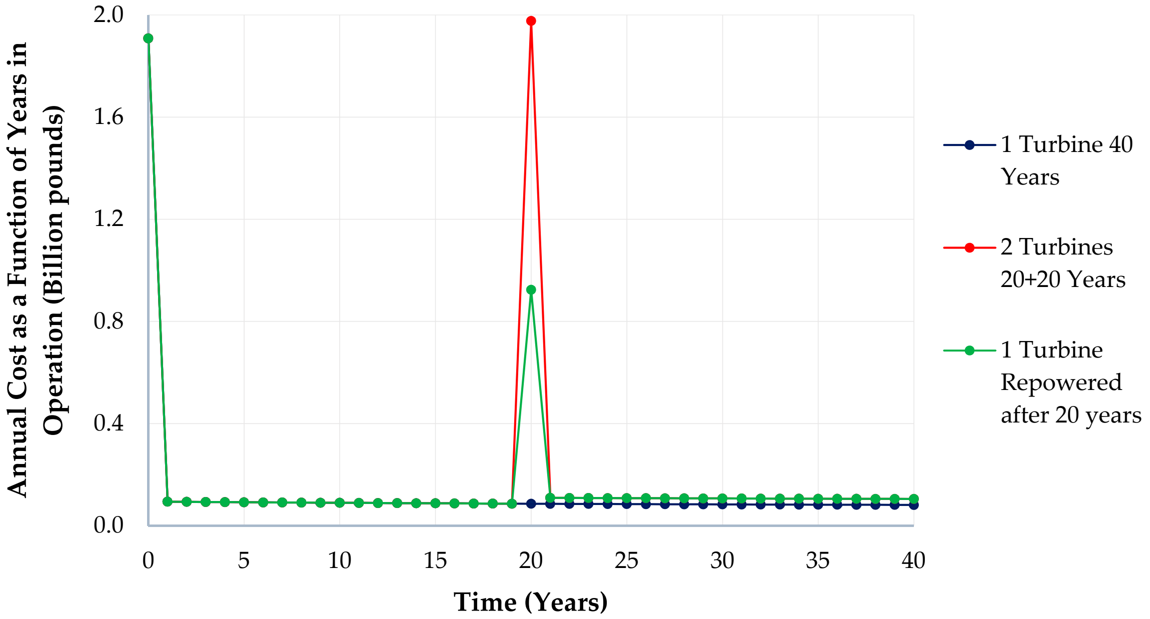

Figure 5. London array comparison between life extension, reinstalling and repowering.

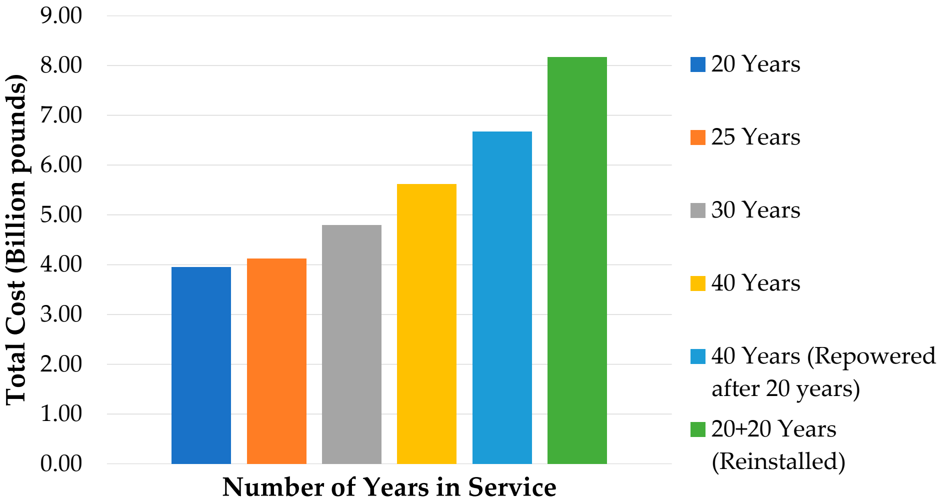

Figure 6. Total Cost over time for different Strategies.

LCOE is the levelized cost of energy which is used throughout the energy generation industry [46]. It is of the cost of 1 MWh in £. The 'Life Extension Cost' an altered version of the LCOE which assumes that all the costs in the first 20 years have been accounted for and from year 21 onwards only new costs are taken into account. This gives a better representation of the financial upside of extending the life of a turbine because it portrays the 'new' £ per MWh.

From the London Array data, the most cost-effective option in the short term is to look at life extension for 5 years. This is not that surprising given that the longer you leave a turbine the more the maintenance cost will go up. It should be noted that repowering offers a good middle ground by having a low life extension cost and will last for another 20 years.

5. Flow Chart of the Proposed Framework for Post-Design Life Decision Making Process

The flowchart in Figure 7 gives a concise overview of this study's proposed framework for post-design life decision-making process in an ageing offshore wind farm. The main three routes have already been discussed: decommissioning, repowering and life extension.

As has been well observed throughout the study, every offshore wind farm is different; hence there is not one correct answer in the decision-making process. This means that the optimum solution must be carefully selected by considering the level of corrosion and fatigue damage in the aged offshore wind turbine structures which could be made possible using the structural health monitoring data.

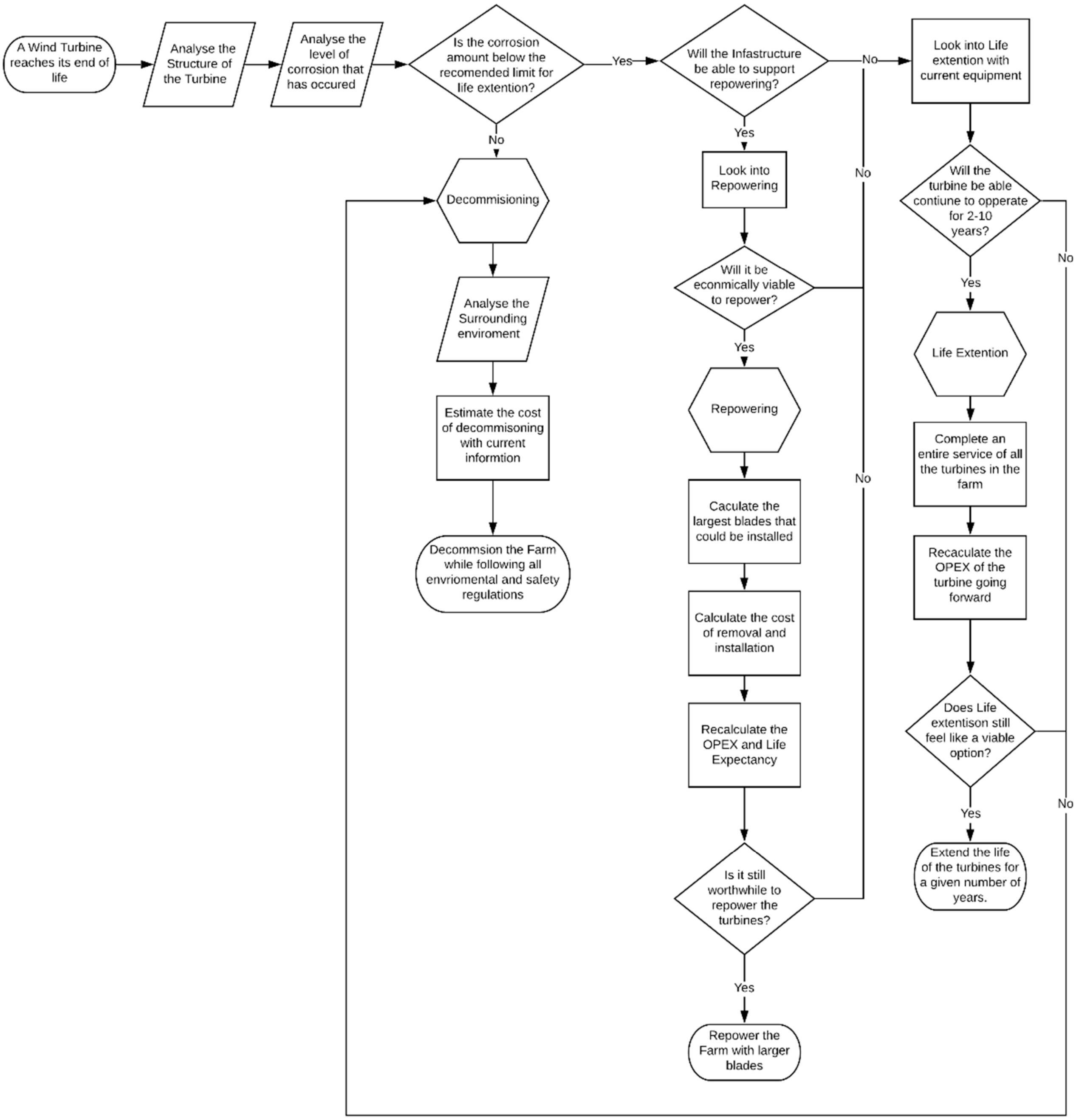

Figure 7. Flowchart of possible routes when looking at ageing offshore wind farms.

6. Discussion

6.1. Decommissioning Challenges

The process of decommissioning has many costs to analyse and consider. As mentioned in Section 3.2.2 estimates for decommissioning are fluctuating wildly from site to site. There are a few reasons for these inconsistencies:

1. Safety and Regulations

Firstly, as discussed, the safety procedures needed to complete the process of decommissioning. These are not just for human safety but also for the environment. It is extremely important in the offshore wind industry that there is effectively no impact on the environment over the life cycle of a wind farm, a position laid out in government and international regulations. Completing any task at sea is difficult, but having to make sure that the lifecycle of every turbine has no impact on the environment is especially difficult when looking 20 years out. So, making assumptions about the costs of working will diverge considerably between operators and promotors across the sector.

2. Public Opinion

The minimal environmental impact is also important to help keep public opinion on their side and thus a favourable subsidy regime is needed.

A major environmental disaster, comparable to an oil spill, or the decommissioning of the Brent Spar storage platform could easily knock back the industry [47]. Some countries with vociferous anti-renewable energy lobbies (e.g., the USA) could be swayed, even though they would be blind to the continual polluting effects of fossil fuel, its extraction and transportation. Given where the world is in energy needs and the passing of peak oil, the whole renewable sector is vital. The environmental issues around this particular sector are more complex than solar and onshore wind—but less than tidal power which is directly attacked by birders and boaters—and so ‘own goals’ must be avoided.

6.2. Life Extension and Repowering Scenarios

As shown in Figures 5 and 6, the use of existing offshore wind infrastructure for electricity production through life extension and repowering at the end of initial design life is a more cost-effective option compared to the commissioning of a new offshore wind farm. This observation is in agreement with those reported by other researchers, e.g., [48,49]. The analysis performed in this study on London Array wind farm shows that by extending the operational life of the existing wind farm using turbines of the same capacity or retrofitted turbines of higher capacities, a significant saving of up to £2 billion can be made in the capital investments. Seen also in Figure 6 is that although the overall cost of life extension beyond 20 years has been found lower than the repowering cost by up to £2.5 billion, the use of retrofitted wind turbines with higher capacities in the second 20 years lifespan in an existing wind farm can produce much more electricity which would justify the need for further investment compared to the cost of life extension. It is worth noting that while repowering is an attractive and cost effective option for the offshore wind industry, it would need resilient offshore wind infrastructure and accurate structural health monitoring systems and structural integrity assessment procedures to ensure that the aged foundations can sustain the larger wind turbines during the extended life period.

6.3. Future Research

This paper has covered well-identified areas to do with decommissioning and life extension, there are a number of additional areas where knowledge is poor and would benefit from additional research. A few suggestions of topics that could be looked into are below:

6.3.1. Pitch Control

Fatigue is a massive issue for wind turbines onshore as well as offshore. If an operator is continuing to use the tower of a wind turbine offshore, where O&M costs are higher, through either life extension or repowering, there need to be improvements to the initial design to help reduce fatigue damage. One way of doing this is pitch control.

Pitch control adjusts the blades by rotating them in the horizontal axis so that their attitude to the wind to extracts the most power, while ensuring that the turbine does not go over its maximum rotational speed—the maximum fatigue producing event. This maintains the turbine's safety within high winds.

The pitch control observes and corrects the angle of the wind turbine's rotor blades and then controls the rotational speed of the turbine. Although pitch control plays a vital role, it currently accounts for less than 3% of a wind turbine's capital expense [50].

Current thinking is to just rotate the three blades on a tower/nacelle in line with the environmental conditions. Research has been done into individual blade rotation. This has yet to be industry-wide even in newer turbines, but clearly there is almost no pitch control in the first-generation offshore wind. Research needs to be done by looking at the feasibility of retrofitting pitch controls to help extend the life of first-generation offshore wind turbines.

6.3.2. Long-Term Corrosion

As already discussed, corrosion is an important area in offshore structures. While one can look towards the oil and gas sector for how long-term corrosion can be stopped and possible likely outcomes when one leaves a main steel structure in the harsh sea environment for 20 or more years, there is little to no true research in this area specifically for wind turbines.

At present, the major assessment of corrosion is from modelling which estimates the expected rate of material loss. This is more than likely to be incorrect as the specifics of a location will vary from the standardised model. The standard model is unlikely to be correct about the rate of removal; it is most likely going to slow down after several years and could even stop completely once a layer of oxide/sediment has been formed. This could mean that turbines could last for much longer than initially predicted because their coatings and corrosion protection are more efficient than initially expected [40,51].

There is ongoing research into fatigue crack growth and whether corrosion can be a moderating influence on this [10,52–55]. The corrosion dulls the surface continually and therefore can slow and even stop initial sharpening and crack growth. This research is extremely new and has yet to be assessed in wide scale observations.

Real life practical examples of long-term corrosion need be assessed in laboratory settings. The dataset of available samples is small and so accelerated experiments may be the best way to collect some. Moreover, ongoing field research is vital so that benchmarks at time points are created. This will create a knowledge base which can be used to set standards for the whole industry and allows O&M operators to gauge specific turbines and farms against their peers/contemporaries.

6.3.3. Digitising O&M

As the offshore wind industry matures, so also does the world around it. When first-generation turbines where being installed, the standard internet connection was via dial-up and had extremely low bandwidth and reliability. The advances in computing and connectivity are reflected in new installations in offshore wind farms. Nowadays, some companies offer advanced digitalisation solutions to increase the efficiency of O&M strategies in offshore wind energy, effectively using the developments in data manipulation/artificial intelligence and computer modelling to predict turbine maintenance issues before they occur [56]. While these companies are new to the industry, the insight they give existing operators could be vital in extending the life of installed turbines. In common with the need for corrosion data, the more data these companies are able to harvest from the field and real situations the better, as this will improve the whole industry; although unlike academic and 'standards' data this will be less publicly available. Even with this proviso the digitisation and continuous monitoring of farms through the internet needs to continue to the benefit of the whole industry.

6.3.4. Change in Ownership

As well as the digitisation of O&M, a change of ownership as farms near the initial/projected end of life will become more likely. While it has already been discussed that, financially, extending the life of a turbine is going to make more sense than decommissioning and rebuilding, the financing structure and agreements might make it easier to sell the farm when it hits its initially predicted end of life. A change in ownership is common in this scenario in other industries, with the incoming investor paying little to no actual capital for the turbines but taking on all environmental responsibilities. This removes the original company's obligation to decommission the farm, and it gets to write up to profit the decommissioning accruals they have made since the midlife point (as mentioned in Section 3.2.2). The new owners would create a new financial model based around the concepts discussed in this report and would undoubtedly be looking to sweat the assets until they (metaphorically) drop.

It is therefore vital that the financial models are well founded for the opening conditions and assumptions. Thus, the costs of conversion to a repowered/extended farm need to be well understood. This makes it more likely that original owners will still be bearing significant financial risks on the first-generation farms. However, market dynamics dictate that early movers from the financial sector will act as soon as the risk factors can be sufficiently articulated and costed.

7. Conclusions

In conclusion, there is no one size fits all process which deals with an offshore wind farm nearing the end of its life. The situational, technical and financial aspects of each wind farm are different. However, it is completely apparent that first generation offshore wind farms should very seriously investigate extension and repowering options rather than accept inevitable decommissioning. The main conclusions drawn from this study are:

- It is more than likely to be financially viable to extend life rather than decommissioning.
- Improvements in data capture and the general increase in sensors and observations mean actually operating wind farms are going to get easier as operators will have better knowledge of the issues turbines will face.
- While there might be some mistakes and economic failures in the first-generation farms, these will enlighten the next generations. So, with the lessons learnt, repowering second and third-generation turbines will be easier and allow them to exploit the whole of their 50-year leases.
- Social attitudes to the offshore wind industry will improve markedly if it can demonstrate a greater efficiency in resource and materials utilisation than when the farms were initially installed. While renewable energy has some detractors, over-delivering environmental benefits in one sector will do the whole industry no harm.

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