Concept for repowering OWF

Comparison of CO_2 and costs with decommissioning

EUROPEAN UNION

Interreg
North Sea Region
Decom Tools
European Regional Development Fund

CONTENTS

LIST OF ABBREVIATIONS

EoL End of Life. 1–3, 5, 6, 9–13

EU European Union. 1

GHG Green House Gas. 9, 12, 13

HR1 Horns Rev 1. 3–10, 12, 13

IRENA International Renewable Energy Agency. 1

IRR Internal Rate of Return. 6, 9, 11

LCoE Levelized Cost of Energy. 6, 7, 9, 11, 13

NPV Net Present Value. 6, 9, 11

OWF Offshore Wind Farm. 1–13

1

INTRODUCTION

1.1. BACKGROUND

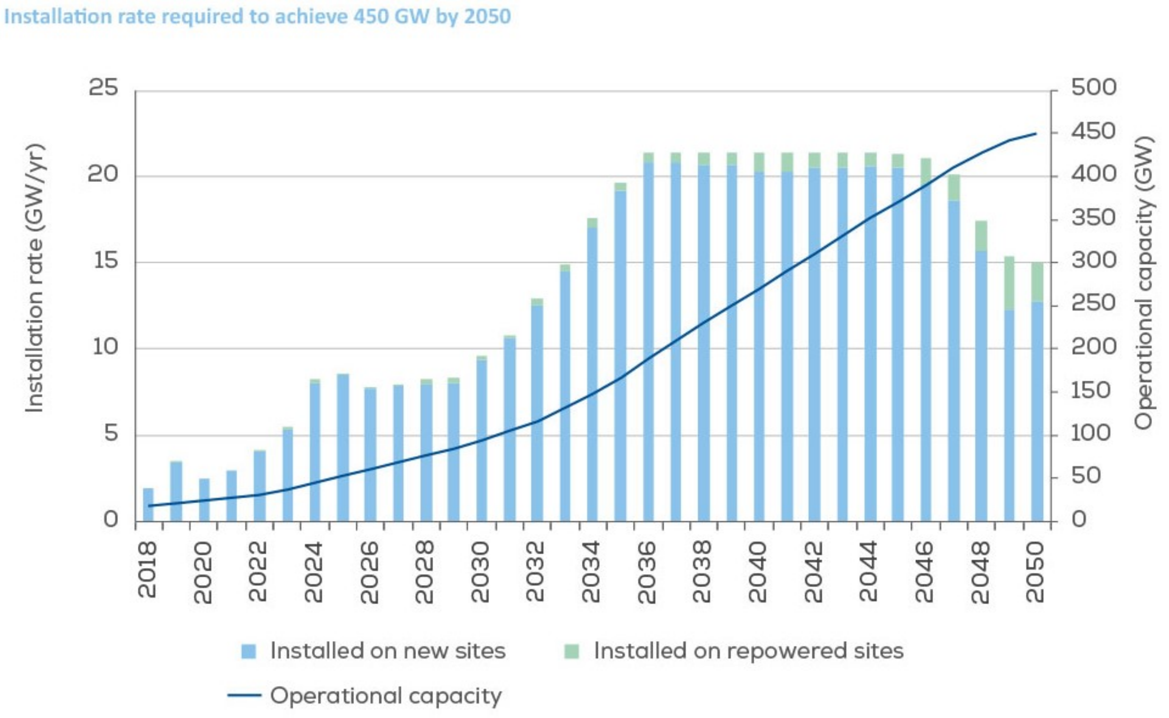
The world today is now facing the adverse effects of the unprecedented human influence on the climate system. Many countries are now transforming their electricity sector with a focus on wind power to meet their climate targets. The International Renewable Energy Agency (IRENA) predicts onshore and offshore wind combined, would generate 35% of the global electricity demand by 2050 [1]. The European Commission estimates installation of 450 GW of offshore wind capacity by 2050 in the European countries, which would meet 30% of Europe's electricity demand [2]. Europe added 2.9 GW of offshore capacity in 2020 and it now has a total installed offshore wind capacity of 25 GW connected across 12 countries [3]. With this surge in installation of new Offshore Wind Farm (OWF) and due to the ageing fleet of currently operating OWF, the number of OWF required to be decommissioned will increase in the coming years. About 3.5 GW of global offshore capacity will reach its designed operational life of 20-25 years by 2035. With 123 turbines already reaching their planned lifetime of 20 years by 2023, the decisions on the End of Life (EoL) scenarios should be researched upon as the problem is soon rising [4].

Currently decommissioning is seen as the default option when an OWF reaches its EoL. It refers to taking down the structures and restoring the site as close to its original state. However, as the development of offshore wind is accelerating and the existing offshore fleet is ageing, it is essential to look into other cost effective and sustainable alternatives for OWF after their planned lifetime. The main scenarios which are currently discussed in the industry are namely:

- Life time extension
- Refurbishment
- Partial Repowering
- Full Repowering
- Decommissioning

These scenarios have certain differences, some of which will be discussed in details in the next chapters. The technical and economic feasibility of considering these EoL scenarios depends on specific wind farm sites and wind farm conditions.

The figure 1.1 shows the annual installation rates and the cumulative capacity to reach the 450 GW Offshore wind target of the European Union (EU). It can be seen that repowering on current existing sites is considered to achieve the target. Till 2025, it is estimated that offshore capacity of 5.0 GW/year will be installed on new sites compared to 0.08 GW/year on repowered sites. Whereas, between 2046-2050, 15.8 GW/year will be installed on new sites and 2.03 GW/year on the repowered locations. Showing a significant increase in the repowering scenario.



Source: BVG Associates for WindEurope

Figure 1.1: Installation rate required to achieve 450 GW by 2050 with repowering contributions [2]

1.2. ONSHORE - OFFSHORE DIFFERENCES

The same issues of EoL scenarios have been raised for the onshore wind turbines, as the onshore wind industry is more mature compared to the offshore wind. The lifetime of the onshore wind farms is extended based on the detailed constant monitoring of structural health. Repowering the onshore wind farms is also seen to be cost effective as using the same area and layout eases the social and environmental impact issues. Further, a possibility of easily upgrading the electricity grid offers flexibility in the approach of onshore repowering. Timely monitoring of remaining life time of structures and inspections are crucial in deciding on the EoL scenarios of wind farms.

The case of OWF is even more complicated with the harsher environments accelerating the wear and tear, corrosion and erosion of components(blades, foundations etc.) Due to harsh conditions and high costs, frequent site visits to analyze the structural health is also difficult. Furthermore the electrical infrastructure is difficult to change without bearing high costs. Thus, even though onshore and offshore technology is comparable till some extent, several factors of differences have the added levels of complexities when analyzing the EoL scenarios of OWF. However, offshore oil and gas industry has some transferable knowledge in maintaining the offshore structures, tackling corrosion and designing offshore structures for longer life that can be implemented in the case of offshore wind industry.

This report gives an overview to some of the EoL scenarios through a techno-economic analysis of an offshore wind farm for a representative case study.

2

END OF LIFE SCENARIOS

Different End of Life (EoL) scenarios for the Offshore Wind Farm (OWF) are required when either the turbine reaches its designed technical lifetime, has been subjected to failure or fatigue or no longer satisfies the expectations of the owner. Profitability, performance and reliability of the exiting OWF and cost benefit analysis of different EoL scenarios are necessary to make the optimal decision. There is rather unclear distinctions in existing literature between some of the EoL scenarios. The following are the typical explanations considered in this study.

Lifetime extension can be be termed as performing minimal required activities to keep the OWF functioning beyond its design lifetime.
Refurbishment can be seen as installing refurbished components in place of defective ones.
Partial Repowering can be comparable with replacing few key components with new technology parts.
Full repowering has several interpretations with replacing existing turbines with fully new turbines.
Decommissioning is taking down the wind farm structures.

Due to their close interpretation, especially between life time extension, refurbishment and partial repowering, the terms are used interchangeably in the literature. A few of these EoL scenarios will be analyzed in depth in the following sections.

2.1. CASE STUDY

The decision of optimal EoL scenario depends on each individual OWF. Detailed data of the remaining life of each structure, availability of spare parts, maintenance costs and current regulations is essential in making an informed decision of the best suited EoL scenario. To model a representative case, a techno-economic analysis is conducted for the Horns Rev 1 (HR1) wind farm as a case study. HR1 was selected based on its age, distance to shore and installed capacity of the wind farm. The relatively simple regular grid layout was also considered for the case study since several other wind farms that are subject to repowering in the near future have similar layouts.

HR1 was built in the North Sea by the Danish energy company Eslam. Formerly known as DONG, and now Ørsted. Installed in 2002, HR1 was the world's first large scale OWF at that time with a capacity of 160 MW. In 2005, 60% of the wind farm was sold for 270m to Vattenfall, who is in charge of operations. The table 2.1 lists the important specifications of the HR1 OWF. The wind farm consists of 80 wind turbines of 2 MW each and OWF has an offshore substation for transmission, owned by Energinet, the Danish TSO. The turbines of the HR1 are placed with a spacing of 7D (Rotor Diameters) between the rows and columns of the wind turbine [5].

Table 2.1: Specifications of the Horns Rev 1 (HR1) Offshore Wind Farm (OWF)

Factor	Value	Unit
Wind Farm Owner(s)	Vattenfall(60%) ; Ørsted(40%)	[-]
Substation Owner	Energinet	[-]
Turbine Model	V80 - 2MW	[-]
Number of Turbines	80	[pcs]
Capacity	2	[MW]
Wind Farm Capacity	160	[MW]
Rotor Diameter	80	[m]
Hub Height	70	[m]
Commissioning Year	2002	[-]
Distance from Shore	14	[km]
Water depth	6-14	[m]
Capacity Factor	41.9	[%]

The rough grid layout of the HR1 wind farm can be depicted from the figure 2.1. The wind farm consists of turbines installed in 8 rows and 10 columns. There are 5 array cables which connect the individual wind turbines to the offshore substation which is shown as a yellow coloured square. The wind turbines are interconnected to a 33 kV cable system. The power generated passes to a transformer platform and the voltage is transformed up to 150 kV before the electricity is taken to the shore through a 21-kilometre submarine cable to Hvidbjerg Strand.

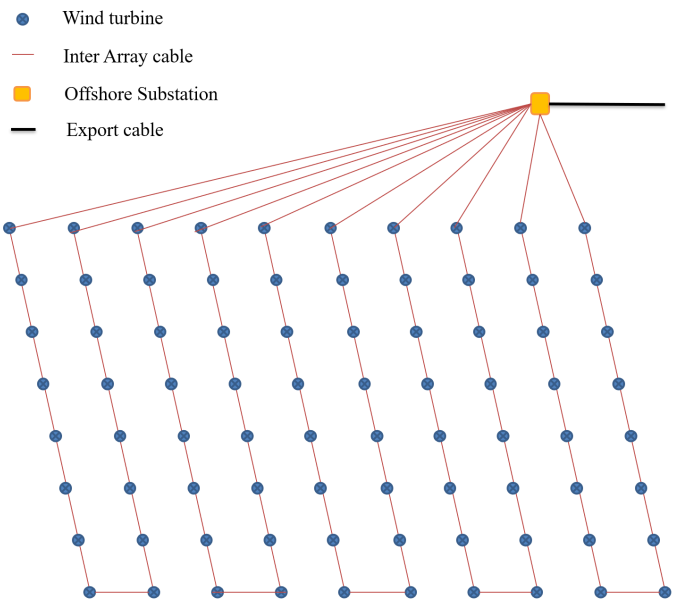
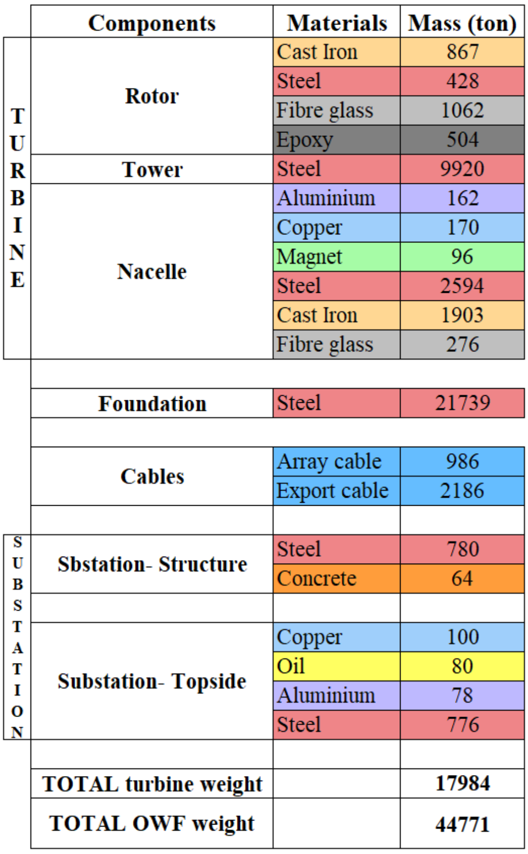


Figure 2.1: Existing grid layout of the Horns Rev 1. Recreated by the author from reference of 4C Offshore database [6]

2.1.1. DATA AGGREGATION

In analyzing the EoL scenarios of the HR1 OWF, data for the analysis is gathered from various possible sources. Majority of the data was collected from the published articles, journals and websites. Qualitative validation of the collected data and more insights into the topic was done through correspondence with the people working in the wind industry. Initially the weight of the materials used in the HR1 OWF were gathered through the study conducted on decommissioning [7]. The substation weights were calculated after interview interaction with Energinet and validated via online research papers [8]. Further data of the cost estimates of different scenarios was gathered from published studies and wherever required assumptions were made. Similarly, the data for calculating the CO_2 impact of the EoL scenarios was aggregated based on open source data bases. The specific data required for each scenarios will be addressed when discussing the each scenario in detail in the following sections.



	Components	Materials	Mass (ton)
TURBINE	Rotor	Cast Iron	867
		Steel	428
		Fibre glass	1062
		Epoxy	504
	Tower	Steel	9920
	Nacelle	Aluminium	162
		Copper	170
		Magnet	96
		Steel	2594
		Cast Iron	1903
		Fibre glass	276
	Foundation	Steel	21739
	Cables	Array cable	986
		Export cable	2186
SUBSTATION	Sbstation- Structure	Steel	780
		Concrete	64
	Substation- Topside	Copper	100
		Oil	80
		Aluminium	78
		Steel	776
	TOTAL turbine weight		17984
	TOTAL OWF weight		44771

Figure 2.2: Authors analysis [7] to calculate Weights of the materials with HR1 OWF parameters

Apart from the material mass estimates of the wind farm, the analysis focused on the economic feasibility of the EoL scenarios. The first generation OWF were supported by different government subsidy schemes, that enabled the OWF to generate additional revenue. The extra support on top of the varying electricity price is generally effective till a certain agreed upon duration. But following the current trends towards zero subsidy OWF, it is very likely that extending the lifetime of the OWF, it has to run solely on the fluctuating electricity market prices. The table 2.2 lists the forecasted day-ahead electricity market price that the HR1 OWF would be receiving. For the purpose of the analysis, an average yearly price is considered and for years from 2031-2050, average of preceding years is taken into account, due to lack of forecasted data.

Table 2.2: Forecasted day-ahead electricity market price in Denmark (DK2 region) [9]

Operations	[Year]	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031 - 2050
Power price, real	[EUR/MWh]	46	48	50	52	53	52	51	50	50	49	50

The key financial parameters were analyzed for the considered scenarios in this work, the table 2.3 lists the common input values that were considered for a financial feasibility analysis of all the EoL scenarios. These values along with the scenario specific values were used to compute the key financial figures of Levelized Cost of Energy (LCoE), Net Present Value (NPV), Internal Rate of Return (IRR) and Payback time. Apart from these key financing values, the OPEX costs for all the scenarios was also assumed to be of 22 €/MW/h [10].

Table 2.3: Common financial assumptions for all the scenarios

Inflation rate	2.0 % [10]
Discount rate	5.0% [10]
Debt investment share	70.0% [10]
Interest on debt	5.0% [10]
Avg Debt Service Coverage Ratio	1.3 [11]
Tax Rate	22.0% [11]

2.2. SCENARIOS

When considering different EoL scenarios for the OWF, there are certain following general advantages as compared to building up of new OWF:

- Utilization of good windy sites
- Improved technology implementation
- Better grid integration
- Ease of social acceptance

Out of the previously mentioned scenarios, the following sections analyse the scenarios of Life Time extension, Refurbishment and Partial Repowering. These specific scenarios were selected as they are considered to be relevant for the case of HR1 OWF. After discussing the pro and cons of each EoL scenario, a techno-economic feasibility analysis is carried out for the HR1 wind farm and later CO_2 impact of each scenario is calculated and compared with the decommissioning alternative in chapter 3.

There are a few common factors and assumptions made that are essential for all the following EoL scenarios. The most important is of the structural stability and remaining life of the structures, it is crucial to analyze in detail the structural life of components for the safe operation of the OWF beyond its design lifetime. When testing for structural stability the load-bearing components are evaluated from foundations to the rotor blades. Analytical methods and physical inspections are conducted before selecting the feasible EoL scenario. As the exact data of the HR1 OWF was not been made available for this analysis, this work is based on reasonable assumptions, expert feedbacks and data gathered through online sources.

2.2.1. LIFE TIME EXTENSION

Life Time extension is defined as the operation of the wind farm for more years than its designed life and relies on the remaining life of structures [12]. The wind farm is kept in operation by doing only minor and low cost repairs. A thorough analysis of the wind turbine components is essential to estimate the remaining life and maintenance strategies. Typically, a cost-benefit analysis is done to see whether repairing a certain component to extend the operation of the turbine is financially feasible. Assessment of the remaining structural strength of each individual wind turbine and its foundation is carried out to finalize which turbines can be kept running. A global study on the development of LCoE showed that an offshore wind farms life can be potentially extended by up to 50% based on an average operational lifetime of 20.3 years [13].

For the case of HR1, it was assumed that the lifetime of the wind turbines can be extended by upto 10 years after their design lifetime. This was assumed based on the fact that as HR1 OWF was one of the first 'large-scale' OWF at the time of its development, most of the structures were over-designed with a higher factor of safety due to the limited experience then. Even though some wind turbine could have to be shut down due to high maintenance/repair costs, for simplistic and comparable purposes, it was assumed that all 80 turbines in HR1 would be operational in the span of extended 10 years. An additional CAPEX costs for the repair and maintenance works of each turbine was assumed after speaking with people in the wind industry. A cost of **150000 €/MW** was considered to keep the turbines operating for extended **10 year** period. This highly depends on the actual state of the asset thus the CAPEX can vary significantly. A slightly lower **capacity factor of 41%** was assumed when considering the life time extension scenario, compared to 41.9% of existing HR1 [14]. This decrease in the turbine performance is due to the ageing of the turbines and potentially additional downtime and maintenance works required.

2.2.2. REFURBISHMENT

Refurbishment in the present literature is often used interchangeably for either Life time extension or Partial repowering. In general Refurbishment is defined as "*Returning used products to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components*" [15]. Refurbishment in this analysis refers to replacement of some major components (Rotor, Nacelle) with refurbished components to further prolong the life of the asset.

For the case of HR1, it was assumed that the rotor and the nacelle which are the main components that limits the life time extension, to be replaced with refurbished Vestas V80 components. Since this is a relatively common wind turbine, it is assumed that there will be refurbished alternatives and spare parts of this model in the near future. It was assumed that replacement by these refurbished key components will extend the life of the wind turbines upto **15 years**. An additional **CAPEX of 903000 €/MW** mainly for the purchase of additional components and their installation was assumed [10]. As the capacity of the OWF is kept same, the existing electrical infrastructure will be utilized for the extended period. Apart from these components, software and controller upgrades will be done for better performance optimization of the turbines. It is thus assumed that these factors result in a higher **capacity factor of 46.2%** for the extended period [10], compared to a 41.9% for the existing HR1 OWF [14] .

2.2.3. PARTIAL REPOWERING

Repowering in general signifies either replacing entire wind turbine system components (full repowering) or upgrading older turbines or specific components (rotor, gearbox) with advanced and efficient technologies while still retaining possible existing infrastructure [1]. So far the only OWF repowering done is of a Swedish OWF Bockstigen. In 2018, Momentum Group A/S performed the partial repowering of 5 550kW turbines at Bockstigen, they were replaced with refurbished blades and nacelles of Vestas V47-660kW turbines, thus increasing the capacity of the OWF [16]. This resulted in almost doubling the energy production, generating profits in the extended lifetime phase. Repowering depends highly on various other factors like the need of renewed permitting, availability of lease areas and the electricity offtake agreements, hence it should be assessed case by case basis.

For the case of HR1, the existing 2MW wind turbines were considered to be replaced with 50 new Vestas V90 3MW turbines. Changing the rotor, tower and nacelle combined with software and controller upgrades was considered for partial repowering. It was assumed that the current foundations of the HR1 would be able to support the 3MW turbine's added loads. This was assumed as Kentish Flats OWF which has the V90 3MW turbines, are supported by monopile foundation with same diameter as HR1, and about the same length and piling depth [17]. In order to use the existing electrical infrastructure (array cables, substation) partial repowering with 50 new turbines was considered. The same electrical infrastructure can be used if the capacity connected to each array cable string is below the existing capacity. The HR1 OWF has 5 array strings each connected to 32MW as seen from figure 2.1. Thus to keep the total capacity withing this value, 10 V90 3MW turbines can be connected to each array string. This gives a total limitation of 50 V90 turbines connected to the repowered HR1 OWF. The figure 2.3 shows the proposed rough layout of the 50 new V90 turbines. The layout is spread as much as possible to minimize the wake effects from a higher capacity turbine. As a higher capacity turbine was used in the same site location, there would be an increase in the wake losses due to the larger rotor diameter, hence a **capacity factor of 40.6%** was assumed [10].

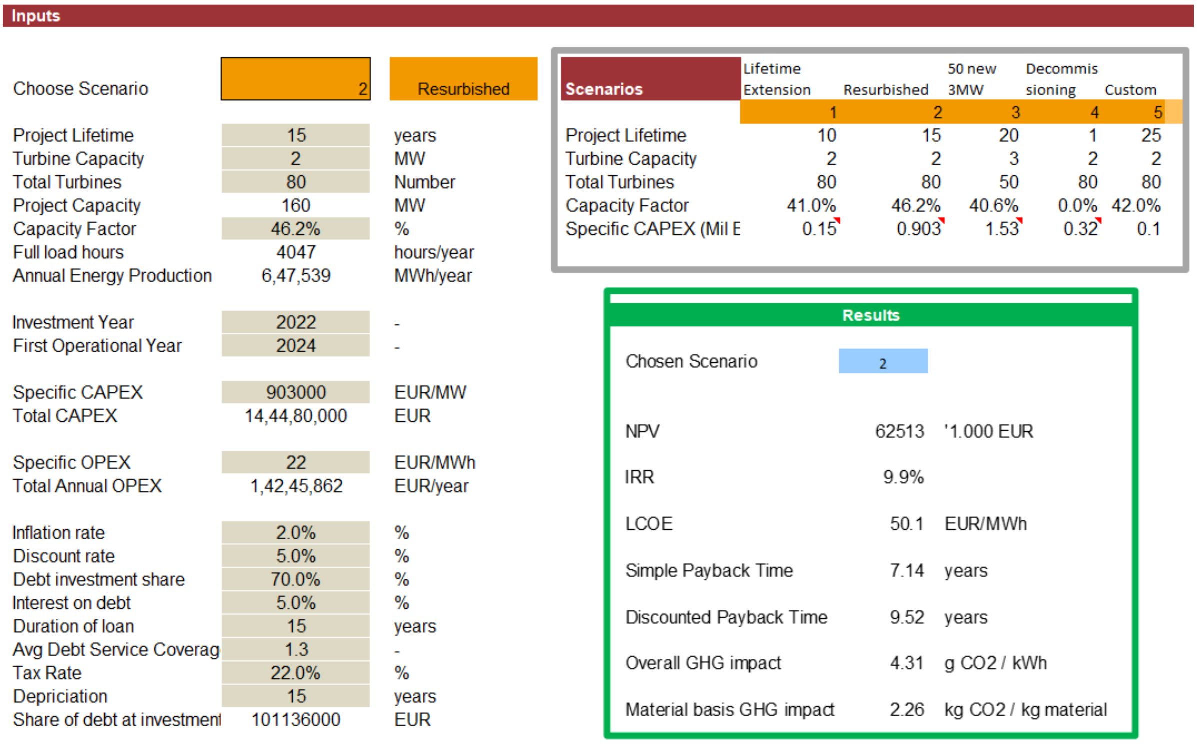
Figure 2.3: Authors depiction of new layout to install the 3MW turbines in repowering scenario

It was assumed that the even though the towers will be replaced, the turbine will have the same hub height. This limitation was mainly due to the load bearing capacity of the foundations, an increase in the tower height inturn increases the bending moment created at the base of the foundation. For this scenario an additional **CAPEX of 1530000 €/MW** was assumed which included the cost of buying the 50 new turbines their installation and a strengthening and retrofitting costs of the existing infrastructure including the foundations [10]. As the turbines to be used are new, an extended lifetime of **20 years** is assumed in this scenario.

2.3. ANALYSIS

The figure 2.4 shows the screen shot of the summary sheet of excel tool developed in this study. In the background of this dashboard, a detailed financial model calculates the main financial parameters like LCoE, NPV, IRR, and Payback time. Further the overall GHG impact is calculated based on the material used in the selected scenarios and the electricity production. The dashboard shown allows the user to see the summary of the analyzed scenario to the user with key results and the input parameters that the user can feed in. As the final decision of the EoL scenarios depends on the case specific data, the excel tool allows the user to input the parameters depending on the considered OWF. This offers the opportunity to get close to accurate representation of the scenario. The customizability of this integrated tool forms a key advantage of the tool, giving the user a quick representation of the EoL scenario depending on the expected level of detail.

Note: The financial analysis is done for the phase of EoL scenarios and the costs and revenue generated from the current HR1 OWF is disregarded in this analysis.



Inputs

Choose Scenario	2	Resurbished
Project Lifetime	15	years
Turbine Capacity	2	MW
Total Turbines	80	Number
Project Capacity	160	MW
Capacity Factor	46.2%	%
Full load hours	4047	hours/year
Annual Energy Production	6,47,539	MWh/year
Investment Year	2022	-
First Operational Year	2024	-
Specific CAPEX	903000	EUR/MW
Total CAPEX	14,44,80,000	EUR
Specific OPEX	22	EUR/MWh
Total Annual OPEX	1,42,45,862	EUR/year
Inflation rate	2.0%	%
Discount rate	5.0%	%
Debt investment share	70.0%	%
Interest on debt	5.0%	%
Duration of loan	15	years
Avg Debt Service Coverag	1.3	-
Tax Rate	22.0%	%
Depriciation	15	years
Share of debt at investment	101136000	EUR

Scenarios	Lifetime Extension	Resurbished	50 new 3MW	Decommis sioning	Custom
	1	2	3	4	5
Project Lifetime	10	15	20	1	25
Turbine Capacity	2	2	3	2	2
Total Turbines	80	80	50	80	80
Capacity Factor	41.0%	46.2%	40.6%	0.0%	42.0%
Specific CAPEX (Mil E	0.15	0.903	1.53	0.32	0.1

Results

Chosen Scenario	2	
NPV	62513	'1.000 EUR
IRR	9.9%	
LCOE	50.1	EUR/MWh
Simple Payback Time	7.14	years
Discounted Payback Time	9.52	years
Overall GHG impact	4.31	g CO2 / kWh
Material basis GHG impact	2.26	kg CO2 / kg material

Figure 2.4: Screen shot of the excel tool dashboard developed by the author

The main uncertainties of the discussed EoL scenarios lies in the CAPEX estimates, predicted lifetime of the scenario, capacity factor and the electricity price. The final result is sensitive towards a variation of these parameters, thus the coustomizability of the developed tool further helps the user to tweak the parameters and see the impact on future scenarios.

The EoL scenarios discussed earlier for the HR1 OWF are analyzed by using the developed tool and the results are discussed in the next chapter.

3

Discussion and Results

This chapter discusses the key results of the analysis done for the EoL scenarios discussed earlier. The table 3.1 lists the key inputs and the results of all the scenarios assessed in this study. Where the scenarios analyzed are as follows:

- Scenario 1: Life time extension
- Scenario 2: Refurbishment
- Scenario 3: Partial Repowering
- Scenario 4: Decommissioning

Table 3.1: Summary table of the key inputs and results for all the EoL scenarios of HR1 OWF.

Factor	**Unit**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Wind Turbine Model	[-]	Vestas V80	Vestas V80	Vestas V90	Vestas V80
Wind Turbine Capacity	[MW]	2	2	3	2
Rotor Diameter	[m]	80	80	90	80
Hub Height	[m]	70	70	70	70
Number of Turbines	[pcs]	80	80	50	80
Total Installed Capacity	[MW]	160	160	150	160
Capacity Factor	[%]	41.0	46.2	40.6	0
Annual Energy Production	[MWh/year]	574656	647539	533484	0
Project Lifetime	[years]	10	15	20	1
Specific CAPEX	[M€/MW]	0.150	0.903	1.53	0.32
Specific OPEX	[€/MWh]	22	22	22	22
Inflation rate	[%]	2	2	2	2
Discount rate	[%]	5	5	5	5
Debt investment share	[%]	70	70	70	70
Interest on debt	[%]	5	5	5	5
Duration of loan	[years]	10	15	20	1
Avg Debt Service Coverage Ratio	[-]	1.3	1.3	1.3	1.3
Tax Rate	[%]	22	22	22	22
Depreciation	[years]	10	15	20	1
NPV	['1.000 €]	94777	62513	-2191	-51200
IRR	[%]	44.8	9.9	4.9	-
LCOE	[€/MWh]	32.10	50.08	64.83	-
Simple Payback Time	[years]	1.51	7.14	12.29	-
Discounted Payback Time	[years]	1.69	9.52	-	-
Overall GHG impact	[g CO_2 / kWh]	4.98	4.31	5.60	6.84
Material basis GHG impact	[kg CO_2 / kg material]	2.25	2.26	2.25	2.25

The analysis is done and several parameters were assessed to compare the different EoL scenarios. The following sections highlight the the preferred alternatives under a few key parameters.

3.1. DECOMMISSIONING

Decommissioning is defined as “*All the measures performed to return a site close to its original state as is reasonably practicable, after the projects lifecycle reaches to an end*" [18]. Irrespective of any EoL scenario considered, the OWF eventually will have to be decommissioned. So a cost-benefit analysis of the discussed EoL scenarios with the decommissioning alternative portrays the benefits that can be gained considering such EoL scenarios. The cost of performing the decommissioning and the potential revenue generated by selling the materials as a scrap was assumed to be be **320000 €/MW** [4]. All the turbines were considered to be decommissioned along with the electrical infrastructure. This resulted in a negative NPV, indicating that wherever possible effort to implement one of the EoL scenarios should be implemented.

3.2. TECHNOLOGICAL SIMPLICITY

The different EoL scenarios discussed have varied complexity levels. Various factors like the remaining life time of components, availability of spare parts, additional permitting procedures add on to the level of uncertainty while performing a certain scenario. Of the discussed EoL scenarios, the **Life Time Extension can be seen as technologically simple** as it primarily involves repairing and maintaining the components. In a partial repowering scenario, the turbines are taken down and higher capacity turbines are installed on top of the foundations, additionally foundation strengthening operations could be required. This makes the partial repowering scenario technologically complex and intricate.

3.3. COST COMPARISON

The key financial parameters that were calculated for all the scenarios are showed again in the table 3.2. It can be observed that **Scenario 1 (Life Time Extension) is the most preferred financial alternative** with an NPV of around 95m €. This scenario also resulted into a highest IRR and lowest LCoE indicating a better business case. The CAPEX can be recovered back fully withing 1.5 years in this scenario. The primary reason for this is the low CAPEX compared to the additional lifetime of the wind farms. The scenario of refurbishment was also seen to be feasible but with a lower NPV. Partial repowering was considered to be infeasible with a negative NPV. This was due to a large investment required to keep the OWF in operation.

Note: It is crucial to note that changes in the electricity price, capacity factor and years of operation have a big impact on the investment decision and they should be thoroughly analyzed before confirming any decision.

Note: The decommissioning costs are not included in the scenarios 1,2,3, however, the cost impact will be similar in all the discussed cases.

The decommissioning scenario was seen to be the worst performing, as there was only a minor one time revenue generation by selling the materials as scrap, as opposed to the continuous revenue generation by electricity generation in other cases.

Table 3.2: Key financial parameter results for all the EoL scenarios of HR1 OWF.

Factor	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
NPV	['1.000€]	94777	62513	-2191	-51200
IRR	[%]	44.8	9.9	4.9	-
LCOE	[€/MWh]	32.10	50.08	64.83	-
Simple Payback Time	[years]	1.51	7.14	12.29	-
Discounted Payback Time	[years]	1.69	9.52	-	-

3.4. GHG Impact

As the sustainability of the wind industry is gaining further attention, a simple comparison of the Green House Gas (GHG) impact of the different scenarios was assessed. The CO_2 emissions of the addressed EoL scenarios was calculated and their results can be seen as in table 3.3. The emissions are calculated for the different stages of the wind farm. For this analysis, the GHG impact from building the existing HR1 OWF, decommissioning all of its structures and the additional emissions by the selected EoL scenario with its decommissioning was included. Primarily about 80% of the total emissions are from the material production and manufacturing components. The remaining is generated by the installation and dismantling. There is a saving of around 25% in the emissions by considering the recycling credits [19]. For the methodology of this analysis, the emissions were calculated with an added material point of view, where the emissions of the EoL were added on top of a reference case of existing HR1 OWF.

Table 3.3: Analysis results for the GHG impact of all the EoL scenarios of HR1 OWF.

Factor	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Overall GHG impact~	[g CO_2 / kWh]	4.98	4.31	5.60	6.84
Material basis GHG impact~	[kg CO_2 / kg material]	2.25	2.26	2.25	2.25

As it can be seen from the table 3.3, the Scenario 2 (Refurbishment) gives the lowest GHG impact. The overall GHG impact, was calculated based on considering the yearly electricity generation for each scenario. In case of decommissioning (Scenario 4), the electricity generated was during the 25 years of operational phase of existing HR1 OWF. This resulted in the most emissions, indicating that in general it is environmentally beneficial to keep the OWF operating for longer. The lower GHG impact in the scenario 2 (Refurbishment) compared to the Scenario 1 (Life Time Extension) is due to the increased production, due to higher capapcity factor and also additional years of production. The second parameter of Material based GHG impact calculates the amount of emissions for a unit of material used in the whole OWF. As the additional quantity of material to be used in the EoL scenarios is not significant compared to the material used in the existing OWF, the values are seen to be comparable. A slight increase for the Refurbishment scenario is due to the additional materials for getting the refurbished components and relatively small change in the years of operation. All these values are lower when comparing to the reference case of existing HR1 OWF which emits 2.79kg CO_2 / kg material used.

4

CONCLUSION AND RECOMMENDATIONS

This study focused on comparing various EoL scenarios that can be considered for future OWF. Taking HR1 OWF as a case study the conducted analysis tried to adapt these scenarios with the parameters of the HR1 OWF showing the differences between different EoL scenarios under different parameters. As a part of this analysis an excel tool was developed which calculated the financial feasibility and GHG impacts of the assessed scenarios. As the decision of selecting the best suited EoL scenario depends on the accurate data of the considered OWF, the tool allows the user to customize with the values known for the OWF in consideration.

As the first generation of the OWF are soon approaching the end of their design lifetime, the talks about decisions on the EoL scenarios are now considered by the wind industry. So far through the current literature, there is still no clarity on the core definitions when it comes to the EoL scenarios especially for the OWF. The scope of different scenarios is seen to be used interchangeably by the industry. In near future, the regulation bodies and the wind industry should define what is included in the various EoL scenarios. Thus the knowledge gained by such analyses can be helpful in defining common terms across the stakeholders.

Furthermore the regulation and permitting processes for EoL scenarios differ between the countries in Europe. Due to the updates in the environmental consents and other leasing and permitting norms after the first generation of OWF were installed, extending the lifetime of those OWF under the updated regulations could pose further difficulties. A distinction in the cases requiring re-permitting and approving should be defined. A suggestion is that the projects should not be considered as 'new' when no change of the tip height, size or location occurs, hence simplifying the permitting and approval process giving further incentives for the developers to consider them as options. Also going ahead, as the scope of the OWF is extended to a 'full-scope' with the offshore substations developed by the wind farm developers, there could be changes in the outcome of the EoL scenarios depending on the ease of upgrading the electrical assets.

In the conducted analysis for the HR1 OWF, **Life Time Extension was seen as the beneficial financial decision with the lowest LCoE.** This is due to extending the operational period of the asset with minimal effort. While the refurbishment has slightly better climate impact. Several key assumptions regarding the structural health of the components, load bearing capacities, regulations and extent of maintenance work were made while doing in this analysis. However, the decision largely depends on the exact state of the assets which should be assessed for a more accurate decision.

This study showcases the potential of gaining economical and environmental benefits from various End of Life (EoL) scenarios of the Offshore Wind Farm (OWF), and offers base for future detailed analysis.

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