A Life Cycle Assessment of Electricity Production from the IJmuiden Offshore Wind Farm

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***Abstract*— The offshore wind industry continues to push boundaries with larger megawatt (MW) wind turbines. However, their environmental impacts are relatively unknown, as there is a lack of information pertaining to offshore wind farms (OWFs) when compared to those onshore. This study applied a life cycle assessment (LCA) methodology to quantify and analyze the impacts of electricity production from the IJmuiden OWF; additionally, this report sought to understand the impact of critical raw materials (CRMs) utilized in the offshore wind industry. The system boundaries for this LCA were drawn at the delivery of electricity to the Dutch electricity grid; and included the resources, energy, transportation, and waste associated with the installation, operation and maintenance (O&M), decommissioning, and End-of-Life (EoL) for the various OWF components. Three scenarios were modeled; the first scenario modeled the IJmuiden OWF with its baseline technical specifications, the second scenario modeled the OWF with an increased operational lifetime, and the last scenario improved CRM recycling. The global warming potential was quantified at 6.51, 4.89, and 6.43 g CO_2 eq/kWh; the baseline scenario showed a 17% decrease when comparing to the lower bound found in the most recent literature. The results showed that offshore wind turbines account for more than 74% of the environmental impacts across 13 out of 18 impact categories and indicated that an improvement in a wind farm's operational lifetime can significantly reduce its environmental impacts. The third scenario found that by improving CRM recycling a reduction of approximately 1% occurred across all impact categories.**

Keywords: Life Cycle Assessment, LCA, IJmuiden Offshore Wind Farm, Critical Raw Materials

I. INTRODUCTION

By 2050 the Netherlands aims to source all their energy from sustainable sources and hopes for the majority to come from wind and solar energy. The Dutch North Sea presents the perfect opportunity to provide the Netherlands with abundant, cheap, and sustainable energy from one of its greatest resources – wind energy. Additionally, the North Sea offers relatively shallow waters, a strong wind climate, and is situated near ports and infrastructure necessary for offshore wind's deployment [1].

The Intergovernmental Panel on Climate Change has recommended governments and policy makers to utilize LCAs, as they are "a particularly useful methodology for determining total system impacts of a given technology" [2]. Ultimately, LCAs, in the scope of offshore wind electricity production, provide clarity into the most impactful features of an OWF and allow for the quantification of their environmental impacts. This study sought to quantify and analyze the environmental impacts of electricity production from the IJmuiden OWF in the Netherlands.

The IJmuiden OWF is the first of three sites currently being tendered in the Netherlands. These three sites have been designated as a part of the IJmuiden Ver Wind Farm Zone (IJVWFZ): Alpha, Beta, and Gamma. The combined output of these sites will contribute 6 GW of new offshore wind capacity to the Netherlands, supporting the nation's ambitious climate objectives.

In the development framework for offshore wind energy important information about the IJmuiden OWF was found, including the project location, operational lifetime, and method of electrical connection [3]. Technical information regarding wind turbine capacity, rotor diameter, hub height, foundation depth, inter-array cable length, and export cable length were based on assumptions from the most recent literature and expert opinions [4]. Table I, shows the IJmuiden OWF site characteristics.

Table I: IJmuiden OWF Site Characteristics

Domain	Value	Unit
Turbine Rated Power	15	MW
Number of Turbines	134	Items
Distance from Shore	150	km
Annual Energy Production	8973	GWh/year
Wind Farm Capacity	2	GW
Inter-Array Cable Voltage	66	kV
Export Cable Voltage	525	kV
Operational Lifetime	25	years

With the significant development of the offshore wind industry in the EU, questions have been raised regarding the scarcity and ethical supply of CRMs utilized in the manufacturing of wind turbines. A variety of CRMs, including neodymium, ferroniobium, praseodymium, dysprosium, and terbium, can be demanded depending on the wind turbine generator (WTG) type [5]. Most of these CRMs are manufactured in countries outside of the EU, reiterating concerns about their long-term supply and posing questions about how the wind industry can meet the ambitious climate goals outlined by the EU if mineral scarcity becomes more prevalent. The role of critical raw materials in the offshore wind industry was also analyzed in the scope of this report and can be found in later sections of this report.

This LCA modeled three separate cases for the IJmuiden OWF. The first scenario utilized the standard technical specification for the IJmuiden Alpha project site and a 25-year operational lifetime. As a baseline all three cases utilized 134 15 MW offshore wind turbines, their accompanying electrical infrastructure, installation and decommissioning requirements, as well as their EoL waste management. The second scenario modeled the OWF with a 35-year operational lifetime and incorporated additional O&M requirements due to the wind farm's increased operational lifetime. The third scenario assumed an improvement in CRM recycling, which was scaled linearly from the EU's CRM recycling targets. A more detailed explanation of each case can be found in the results and analysis section of this report.

II. METHODOLOGY

The following methodology was applied when performing the LCA for the IJmuiden OWF. The LCA was conducted according to the International Reference Life Cycle Data System Handbook for LCAs which was in accordance with the International Organization for Standardization (ISO) standards 14040 and 14044 – ensuring accuracy and reproducibility throughout the project [6].

A cradle-to-grave analysis was performed which defined the system boundaries for the life cycle assessment as the necessary energy and resources from the extraction of raw materials until the EoL waste management of the offshore wind turbines and electrical infrastructure.

The functional unit for this study was defined as 1 kWh of electricity produced from the OWF and delivered to the Netherlands electricity grid, based on its lifetime generation. It should be noted that this LCA was performed in the scope of the Netherlands, and the 1 kWh of electricity produced is dependent on its location. Additionally, the OpenLCA software was selected to perform the impact assessment and the ReCiPe (H) midpoint impact assessment method was utilized.

This thesis was commissioned by Guidehouse Netherlands B.V.; and performed in accordance with the master's requirements from the Department of Energy Engineering and Management at Instituto Superior Técnico in Lisbon, Portugal.

III. INVENTORY ANALYSIS

This LCA was performed to provide a more accurate account of the environmental impacts caused by the production of electricity from offshore wind farms. Additionally, this LCA sought to answer and improve upon the existing knowledge gaps pertaining to the life cycle assessment of offshore wind electricity production. Much of the existing literature has not considered the impact from CRMs, O&M, or EoL activities. However, since the analysis was to be performed on a large, 15 MW, direct drive (DD) wind turbine, it was important to look at the environmental impacts produced from the extraction, manufacturing, and transport of the critical minerals necessary in the WTG.

The inventory information was compiled from a variety of sources, this included the raw material extraction, refining, and transport; manufacture and assembly of components; O&M, and EoL activities. Much of the pertinent information necessary for the life cycle inventory (LCI) such as number of turbines, transmission distances, and capacity of the offshore substation was provided by the Dutch government's development framework for offshore wind energy [3] and TenneT's consultation for a 2 GW HVDC offshore grid connection [7]. Information about the decommissioning and structural mass of a 15 MW direct-drive (DD) wind turbine was collected from TNO's offshore wind farm decommissioning document [8], and IEA's 15 MW reference turbine document [9]. Figure 1 shows the IJmuiden OWF system model which consisted of the offshore wind turbine, electrical infrastructure, installation, O&M, decommissioning, and EoL.

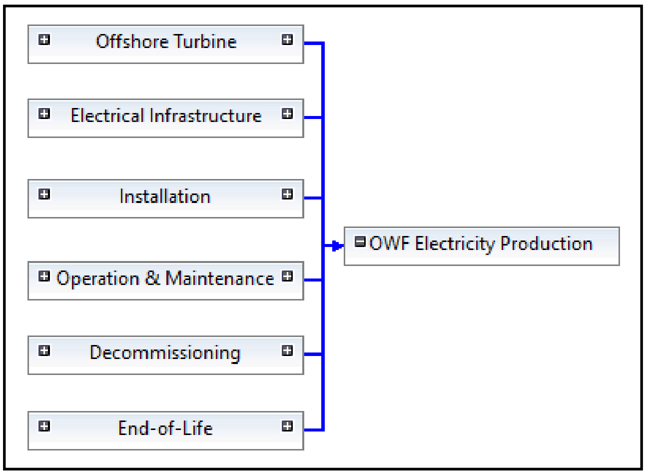

Fig. 1. IJmuiden OWF System Model

A. Offshore Turbine

The IJmuiden OWF utilized 134 15 MW turbines to meet the 2 GW capacity outlined in the development framework [3]. The offshore turbine consists of the support structure, which includes the tower, transition piece (TP), monopile foundation, and scour protection; as well as the rotor nacelle assembly (RNA), which includes the rotor and nacelle. Figure 2, below, shows the offshore turbine system model.

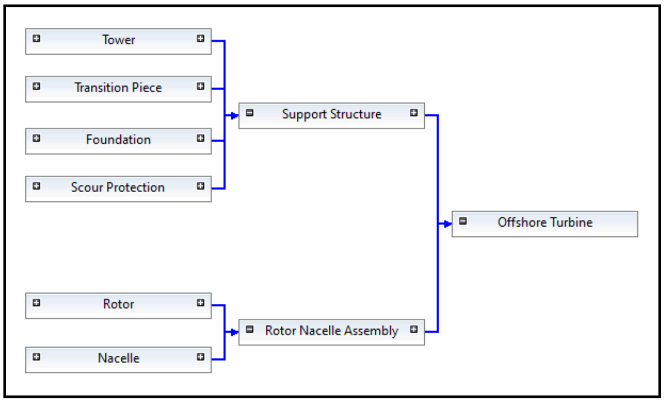

Fig. 2. Offshore Turbine System Model

B. Electrical Infrastructure

TenneT, the Netherlands' transmission system operator (TSO), was tasked by the Dutch government to provide the grid infrastructure necessary for the deployment of offshore wind. As such, TenneT has developed their 2 GW program which seeks to standardize new offshore wind grid installations; the standard includes 66 kV inter-array cabling, 525 kV export cabling, an offshore converter station, and onshore substation – all of which were incorporated into the LCA model. Figure 3 shows the electrical infrastructure system model.

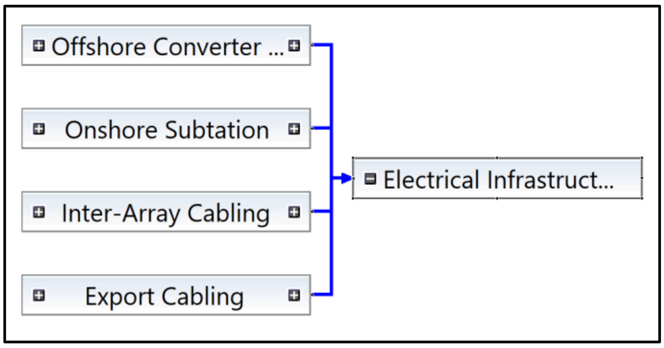

Fig. 3. Electrical Infrastructure System Model

The initial power produced from the wind turbines is transmitted to the offshore converter station through 66 kV inter-array cables. Once the power has been converted at the 2 GW AC/DC converter station, it is then transmitted to the onshore substation through 525 kV export cables. The power is converted again from 525 kV HVDC to 380 kV HVAC and returned to the Dutch utility grid.

C. Installation

The installation of the IJmuiden OWF included the energy and transport associated with all installation activities. Table II, below, shows the percentage contribution of the varying installation activities required as a part of the IJmuiden OWF; a more detailed inventory can be found in the supplemental information of this report.

Table II: Installation Input Percentage Contribution

Input	Contribution
Installation of Scour Protection	42.50%
Installation of Transition Piece	13.36%
Installation of Nacelle	12.36%
Installation of Export Cabling	9.86%
Installation of Rotor	8.14%
Installation of Foundation	6.41%
Installation of Inter-Array Cabling	3.27%
Installation of Tower	2.58%
Installation of Offshore Converter Station	1.15%
Installation of Onshore Substation	0.37%

D. Operation and Maintenance

The IJmuiden OWF is planned to be in continuous operation for a period of 25 years. The O&M strategy for the IJmuiden offshore wind farm was obtained from literature and included the wind turbines' part replacements and associated transportation [10, 11], as well as cable and substation oil replacements [12].

Historically, most of the maintenance related concerns for offshore wind farms has stemmed from the gearbox of offshore turbines [13]. The IJmuiden OWF, however, utilized DD wind turbines which avoided the need for a gearbox. From literature, it was determined that the major maintenance related concerns for DD wind turbines included the replacement of its blades, small parts, transformer, and generator [10, 11]. Both the inter-array and export cabling will require periodic maintenance and require a section of at least 1 km to be replaced for any maintenance work to occur [12]. Table III shows the failure rates for the various OWF components; additionally, the quantity of substation oil required can be found in the supplemental information of this report.

Table III: Installation Inputs Percentage Contribution

Component	Rate	Unit
Blades	0.001%	Failures/turbine/year
Generator	0.0009%	Failures/turbine/year
Transformer	0.077%	Failures/turbine/year
Small Parts	0.362%	Failures/turbine/year
Inter-Array Cabling	0.003%	Failures/km/year
Export Cabling	0.003%	Failures/km/year

E. Operation and Maintenance

The decommissioning of the IJmuiden OWF is similar to that of the installation process, it was assumed that the wind turbines and electrical infrastructure would be removed at the end of the wind farm's operational lifetime. It should also be noted that previously in the offshore wind industry, it was common practice to leave the cabling in the seabed upon a wind farm's decommissioning. However, with the increasing capacity of wind farms, as well as their associated material demand, it has become economically viable to remove and recycle these cables upon their EoL – which was incorporated into the model as a part of the LCI. The only component of the IJmuiden OWF not considered for decommissioning was the gravel utilized for scour protection of both the wind turbines and offshore converter station; ecofriendly scour protection has become the new standard in the Netherlands, and it is left in place upon the wind farms decommissioning [14]. The percentage contribution of the varying decommissioning activities can be found in Table IV, below.

Table IV: Decommissioning Inputs Percentage Contribution

Input	Contribution
Decommissioning of Rotor	14.16%
Decommissioning of Nacelle	21.49%
Decommissioning of Transition Piece	23.24%
Decommissioning of Tower	4.49%
Decommissioning of Foundation	11.15%
Decommissioning of Inter-Array Cabling	5.69%
Decommissioning of Export Cabling	17.14%
Decommissioning of Offshore Converter Station	2.01%
Decommissioning of Onshore Substation	0.64%

F. End-of-Life

A comprehensive review of offshore wind LCA literature and industry best practices was performed to determine the appropriate EoL waste management strategy for the IJmuiden OWF [5, 15, 16]. The EoL modeling for the IJmuiden offshore wind farm was divided into hazardous waste incineration (HWI), municipal waste incineration (MWI), recycling (R), and landfilling (L); Table V shows the EoL methods and ratios for the first scenario; for the third scenario the CRM recycling was improved to 56.7%.

Table V: Method and End-of-Life Ratio

Material	Type of Disposal and Ratio
Sand	L 100%
Epoxy Resin	HWI 100%
Polycarbonate	HWI 100%
Polyester Resin	HWI 100%
Lubricating Oil	HWI 100%
Paint	HWI 100%
Sulfur Hexafluoride	HWI 100%
Boric Oxide	HWI 100%
Hazardous Waste	HWI 100%
Mineral Oil	HWI 100%
Glass Fiber Reinforced Plastic	MWI 100%
Synthetic Rubber	MWI 100%
Cement	MWI 100%
Inert Waste	MWI 100%
Sulfate Pulp	MWI 100%
Dysprosium (CRM)	R 0.3%, MWI 99.7%
Ferroniobium (CRM)	R 0.3%, MWI 99.7%
Neodymium Oxide (CRM)	R 0.3%, MWI 99.7%
Polypropylene	R 100%
Polyethylene	R 100%
Wood	R 100%
Nickel	R 68%, MWI 32%
Aluminum	R 90%, MWI 10%
Copper	R 90%, MWI 10%
Iron	R 90%, MWI 10%
Steel	R 90%, MWI 10%
Lead	R 95%, HWI 5%
Zinc	R 95%, MWI 5%
Silver	R 98%, MWI 2%

IV. RESULTS AND ANALYSIS

In this section, the environmental impacts of producing 1 kWh of electricity from the IJmuiden OWF are presented and discussed. Three scenarios were modeled, and their environmental impacts for the 18 ReCiPe (H) midpoint impact categories can be found in Table VI, below.

Table VI: Decommissioning Inputs Percentage Contribution

Domain	Acronym	Scenario 1	Scenario 2	Scenario 3	Unit
Climate Change	GWP	6.51E+00	4.89E+00	6.43E+00	g CO_2 eq
Terrestrial Acidification	TAP	2.35E-02	1.88E-02	2.31E-02	g SO_2 eq
Ozone Depletion	ODP	1.08E-08	9.78E-09	9.25E-09	g CFC 11 eq
Agricultural Land Occupation	ALO	4.50E-04	3.00E-04	4.10E-04	m^2
Urban Land Occupation	ULO	3.71E-03	2.60E-03	3.39E-03	m^2
Natural Land Transformation	NLT	1.37E-06	1.06E-06	1.25E-06	m^2
Fossil Depletion	FDP	1.80E+00	1.36E+00	1.78E+00	g oil eq
Metal Depletion	MDP	5.37E+00	4.52E+00	5.36E+00	g Fe eq
Water Depletion	WDP	3.27E-05	2.67E-05	3.03E-05	m^3
Freshwater Ecotoxicity	FET	3.15E+00	2.86E+00	3.14E+00	g 1.4 DCB eq
Marine Ecotoxicity	MET	2.74E+00	2.49E+00	2.73E+00	g 1.4 DCB eq
Terrestrial Ecotoxicity	TET	1.23E-03	5.78E-04	9.80E-04	g 1.4 DCB eq
Human Toxicity	HT	9.21E+00	8.12E+00	9.14E+00	g 1.4 DCB eq
Freshwater Eutrophication	FEP	8.34E-03	7.21E-03	8.30E-03	g P eq
Marine Eutrophication	MEP	1.48E-02	1.16E-02	1.03E-02	g N eq
Ionizing Radiation	IR	3.20E-01	2.60E-01	2.30E-01	g U235 eq
Particulate Matter Formation	PMF	1.32E-02	1.11E-02	1.21E-02	g PM10 eq
Photochemical Oxidant Formation	POF	2.48E-02	1.97E-02	2.45E-02	g NMVOC

A. *Scenario 1 Results*

The first scenario modeled the IJmuiden OWF with a 25-year operational lifetime. Figure 4, below, shows the relative contribution of the life cycle processes to each impact category. The total environmental impacts were quantified and can be found in the supplemental information of this report. The GWP was quantified at 6.51 g CO_2 eq/kWh and MDP quantified at 5.37 g Fe eq/kWh for the first scenario.

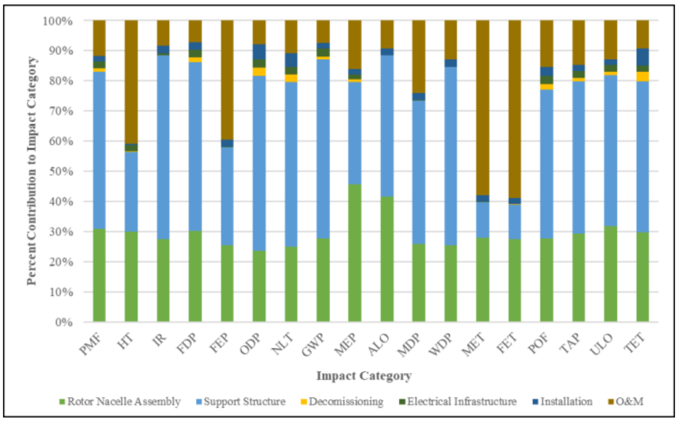

Fig. 4. Scenario 1 – Relative Contribution of Each Life Cycle Process to the Impact Categories

The global warming potential quantified for the IJmuiden OWF showed a 17% decrease when comparing to the lower bound found by Mendecka and Lombardi, 7.8 – 32 g CO_2 eq/kWh [16] and can be explained for several reasons. 80 out of 107 LCAs analyzed by Dolan and Heath reported a wind farm lifetime of 20 years [15]. When compared to the 25-year lifetime of the IJmuiden OWF and the significant increase in AEP, it becomes strikingly evident that larger MW offshore wind turbines can deliver more electricity to the grid with a reduced environmental impact.

B. *Scenario 2 Results*

The second scenario sought to quantify the environmental impacts of the IJmuiden OWF with a 35-year operational lifetime. It should be noted that most of the LCI inputs were kept constant, except for the net total yield and O&M requirements. The net total yield increased from 224,000 GWh to 314,000 GWh, and the O&M inputs were adjusted from 25 years to 35 [5, 15, 16]. However, it should be noted that the annual rates of failure were kept constant with the references and would result in an underestimation of environmental impacts, since the rate of failure is likely to increase after the wind farm's typical lifetime of 25 years. Additionally, the amount of lubricating oil required for the substation maintenance was scaled linearly from 1,750 tons to 2,450 tons.

For the second scenario, the GWP was quantified at 4.89 g CO_2 eq/kWh and MDP quantified at 4.52 g Fe eq/kWh. Figure 5 shows the percentage contribution to each impact category for the 35-year operational lifetime scenario. Additionally, a more detailed impact category breakdown can be found in the supplemental information of this report.

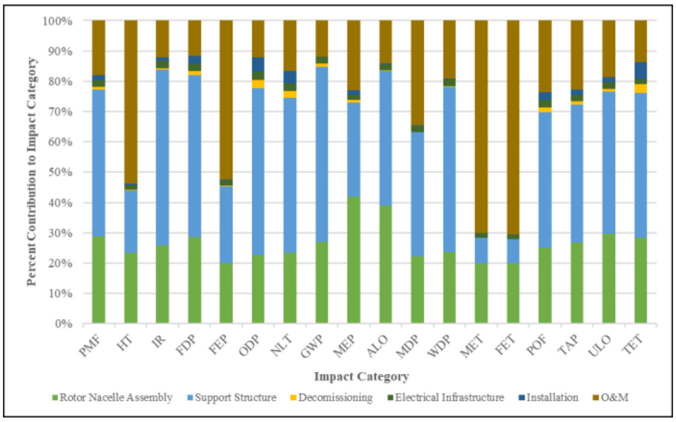

Fig. 5. Scenario 2 – Relative Contribution of Each Life Cycle Process to the Impact Categories

C. *Scenario 3 Results*

This recycling scenario sought to analyze and quantify the environmental impacts from improved CRM recycling. The recycling rates were scaled linearly from 0.3% to 56.7% in 2050, based on the targeted recycling rate of 15% by 2030 [17]. The third scenario quantified the GWP at 6.43 g CO_2 eq/kWh and MDP at 5.36 g Fe eq/kWh. Figure 6, below, shows the relative contribution of each life cycle process to the impact categories.

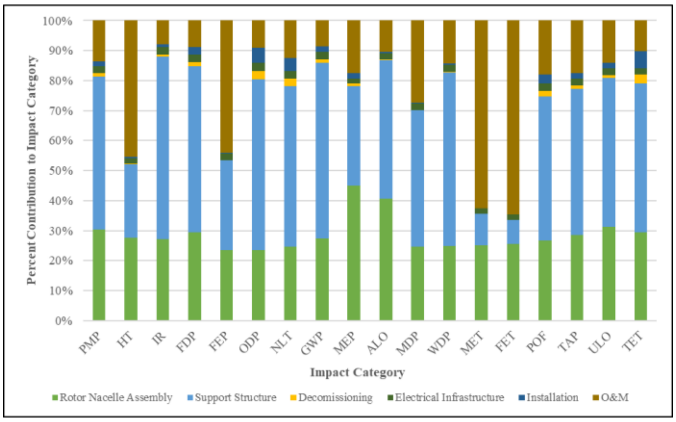

Fig. 6. Scenario 3 – Relative Contribution of Each Life Cycle Process to the Impact Categories

D. *Analysis*

The functional unit of delivering 1 kWh of electricity to the grid in the scope of its associated global warming potential is a benchmark commonly utilized with electricity generation to understand its true environmental impacts. Figure 7 shows the global warming potential for the three cases modeled for the IJmuiden OWF LCA. The first scenario had a GWP of 6.51 g CO_2 eq/kWh, the second scenario had a GWP of 4.89 g CO_2 eq/kWh, and the third scenario a GWP of 6.43 g CO_2 eq/kWh. From this a variety of factors become evident, the first being that the increased AEP from larger MW offshore wind turbines can provide more electricity with the same amount of wind turbines. Although they come with additional material, energy, and transportation demands, these turbines can produce electricity with an overall lower environmental impact compared to the smaller MW turbines [16]. Additionally, the utilization of larger capacity wind farms and HVDC infrastructure allows for more efficient electricity transmission, which explains the reduced environmental impacts.

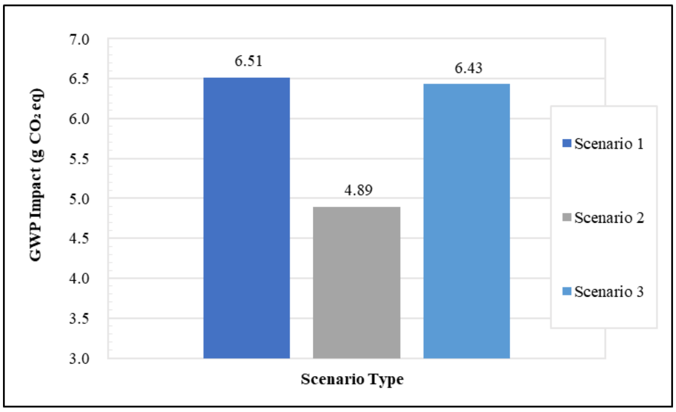

Fig. 7. Global Warming Potential for the Three Scenarios

Metal depletion was another focus area of this LCA. The metal depletion impact category refers to the depletion of metal resources stemming from the production and consumption of a product or service, this impact category considers the finite nature of metal resources and associated environmental consequences from their extraction; this includes habitat destruction, energy consumption, as well as other environmental burdens. Furthermore, the MDP impact category considers all metal resources including the CRMs outlined by the EU. In the light of the EU's Critical Raw Materials Act, the importance of CRM recycling and security will become more important for the renewables sector – as wind turbines, solar panels, and batteries will put additional strain on the CRM's supply chain [17].

The first scenario found a MDP of 5.37 g Fe eq/kWh, the second scenario had a MDP of 4.52 g Fe eq/kWh, and the third scenario a MDP of 5.36 g Fe eq/kWh. When extending the IJmuiden OWF's operational lifetime the MDP experienced a reduction of 16%. Figure 8 shows the quantified MDP environmental impact for all three cases. The improved CRM recycling scenario showed a reduction of less than 1%. Although the reduction in MDP impact was more significant in the second scenario, it is worth noting that a decrease of less than 1% is still considerable. Additionally, the recycling improvement led to a decrease of over 7% across nine other impact categories. Considering the substantial quantity of metals and minerals used during the construction of the IJmuiden Offshore Wind Farm, totaling 624,156 tons, the mass of CRMs accounted for merely 641 tons. Thus, achieving a reduction of approximately 1% in MDP, considering the CRMs' 0.1% mass composition, is a noteworthy accomplishment. This reduction demonstrates the potential impact of efficient resource management and highlights the significance of even small improvements in the sustainability performance of projects of this magnitude.

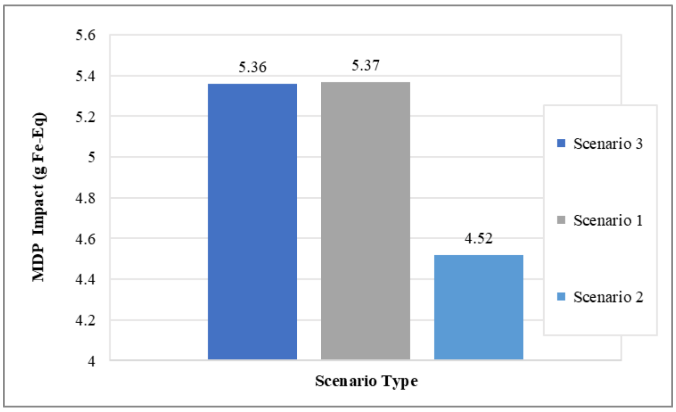

Fig. 8. Metal Depletion for the Three Scenarios

1) Offshore Turbine Analysis: For the first scenario, the offshore wind turbine accounted for more than 74% of the environmental impacts across 13 out of 18 impact categories, primarily due to the significant amount of steel utilized for its construction. Steel has a large environmental impact due to the substantial amount of energy and transport necessary for its manufacturing. For the improved operational lifetime scenario, the environmental impacts across 4 impact categories were shown to decrease by at least 20%, with two impact categories, marine ecotoxicity and freshwater ecotoxicity, shown to decrease by 29%.

The offshore wind turbine's first tier of inputs consisted of the RNA and support structure. When broken down further the offshore wind turbine was comprised of the base plate, DDPMG, nacelle cover, yaw mechanism, blades, DD shaft, monopile foundation, scour protection, tower, TP, as well as its assembly; Figure 9, on the next page, shows the global warming potential for the second tier of inputs for the offshore wind turbine.

The foundation contributed the vast majority share of the global warming potential for the offshore wind turbine, followed by the tower, DDPMG, and TP. Since the material inputs, transport, and energy requirements are similar for the monopile foundation, tower, and TP it can be assumed that the environmental impacts are closely linked with the overall mass for these various components. The mass of the monopile foundation was quantified at 2,000 tons; the tower at 805 tons; and TP at 500 tons. Its associated global warming potential was quantified at 1.64 g CO_2 eq, 0.72 g CO_2 eq, and 0.41 g CO_2 eq, which indicates that the mass of iron and steel contributes a significant amount to its environmental impacts.

2) Electrical Infrastructure Analysis: In the first scenario the electrical infrastructure comprised 2% of the environmental impacts for 11 out of 18 impact categories, with the largest impact, of 3%, stemming from four impact categories: fossil depletion, ozone depletion, natural land transformation, global warming potential, and photochemical oxidant formation. 6 impact categories, ionizing radiation, agricultural land occupation, metal depletion, water depletion,

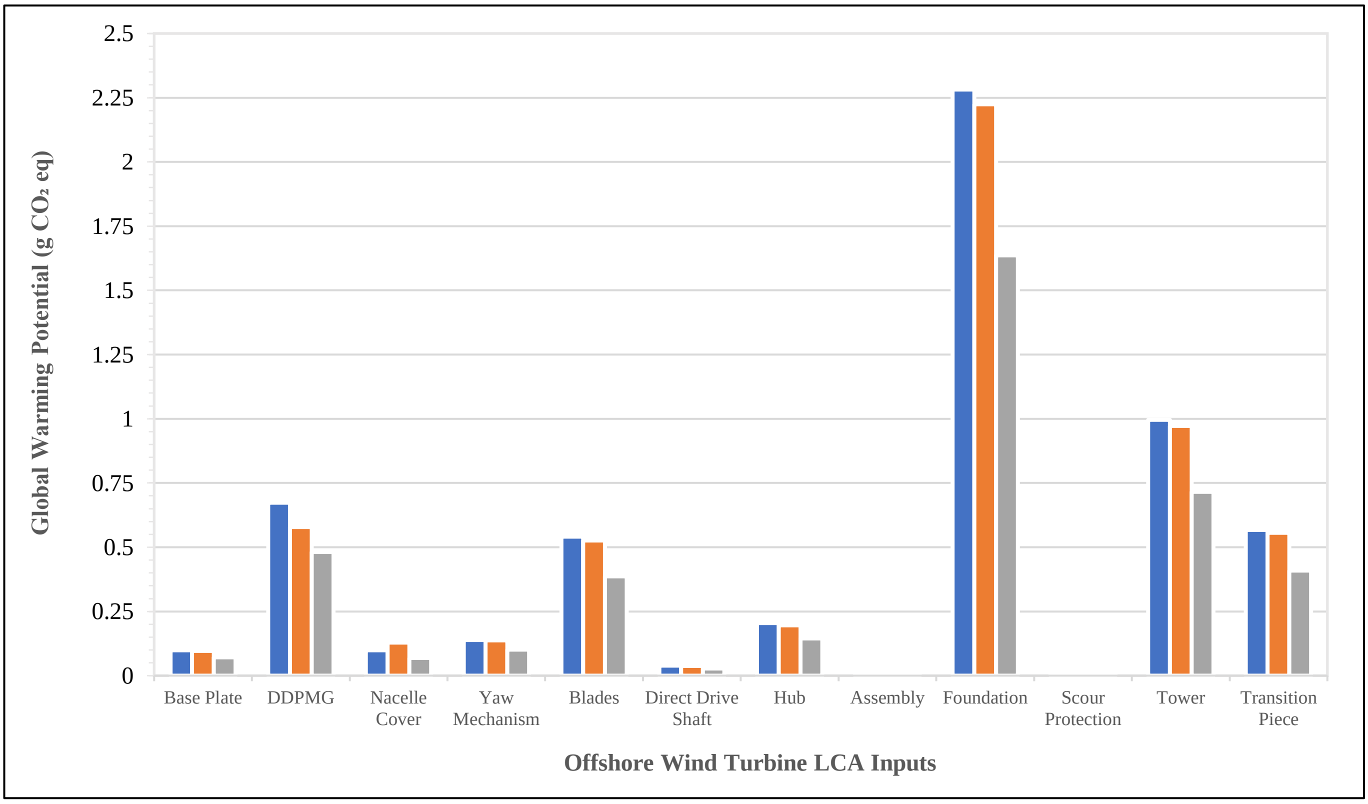

Fig. 9. Offshore Wind Turbine Global Warming Potential Environmental Impacts

marine ecotoxicity, and freshwater eutrophication, had less than 1% of the total impact. For the second scenario, these 6 impact categories increased to 2%, while the remaining impact categories had a minimum decrease of 4%. In the third scenario 7 impact categories showed an increase, with the other 11 categories showing a decrease of at least 1%.

3) Installation Analysis: The installation of the wind turbine and electrical infrastructure accounted for at least 2% of the total environmental impacts for 17 out of 18 impact categories. When comparing the improved operational lifetime to the first scenario, the environmental impacts saw a reduction of more than 5% across 16 impact categories. The third scenario saw a 2% decrease in environmental impacts across 6 impact categories.

4) Operation and Maintenance Analysis: O&M, for the first scenario, was the largest contributor to the environmental impacts for marine ecotoxicity and freshwater ecotoxicity, with 58% share across both impact categories. In the second scenario O&M showed a significant increase in environmental contribution across all 18 impact categories, with the lowest increase of 21% for the marine ecotoxicity and freshwater ecotoxicity impact categories. This can be primarily attributed to the fact that across these two categories O&M represented the largest share of impacts. 8 of the impact categories showed an increase of at least 50%, with the largest increase of 66% in the fossil depletion impact category. For the improved CRM recycling scenario O&M showed a decrease across all 18 impact categories, with 14 impact categories showing a decrease of at least 20%. The largest decrease in impact occurred in the ionizing radiation impact category with a decrease of 36%.

5) Decommissioning Analysis: The environmental impact percentage contribution obtained for decommissioning is similar to that obtained for installation. 10 of the impact categories accounted for at least 1% of the total impact, with three categories, ozone depletion, natural land transformation, and terrestrial eutrophication having a 3% share. The extended operational lifetime scenario saw a decrease in 15 out of 18 impact categories; and the improved CRM recycling scenario saw a decrease in 17 out of 18 impact categories, minus ionizing radiation, which increased from 0% to 1%. One of the only components of the IJmuiden OWF which was not considered for decommissioning was the scour protection. It was notable, however, that while a significant quantity of scour protection was required for the IJmuiden offshore wind farm, 652,904 tons, the environmental effects were found to be less than 1% of emissions across 15 out of 18 impact categories.

V. FUTURE WORK AND RECOMMENDATIONS

The following section outlines the areas of future work and recommendations identified from this LCA. It is recommended that the offshore wind industry look to increase the operational lifetime of OWFs, improve material recycling rates, and look for technological improvements such as the transition pieceless monopile; which in the case of the IJmuiden OWF, the TP accounted for more than 9% of the total global warming potential.

The first identified area of interest for future work pertains to an offshore wind farm’s decommissioning and EoL. The EoL recycling rates for most of the metals utilized in the IJmuiden OWF, such as iron and steel, were quantified at 90%, based on current industry best practices [5, 15, 17]. This estimation is on the conservative side, as technological improvements in the industry have enabled developers to remove larger sections of the monopile upon its decommissioning; further work should be performed to identify the additional percentage of steel which can be recuperated upon a wind farm’s decommissioning.

Additionally, the 35-year operational lifetime scenario utilized the same rates of failure for the various OWF components as the 25-year operational lifetime scenario [10-12]. This, however, is not entirely accurate and would result in lower emissions and an underestimation of component failure; it is more than likely that these components would experience significantly increased rates of failure past their intended operational lifetime, and further work should be performed to determine the appropriate component failure rates as well as their associated environmental impacts.

Another notable focus area for future work can be found regarding the quantification of the impacts from HVDC transmission and its required infrastructure. The material inputs as well as energy and transportation requirements for the IJmuiden OWF’s offshore converter station were based on literature from an HVAC offshore substation and scaled accordingly [19]. HVDC infrastructure, however, has increased infrastructure requirements and further research should be performed to provide a more detailed account of the environmental impacts from HVDC transmission [20].

VI. CONCLUSION

The objectives of this LCA were to quantify and analyze the environmental impacts of producing 1 kWh of electricity from the IJmuiden OWF. The Netherlands aims to have a total offshore wind capacity of 21 GW by 2030 and seeks to reduce their emissions by 55% compared to 1990 levels. They have laid the foundation to achieve these ambitious goals by enabling TenneT with the necessary means to construct and operate the offshore electricity grid [3]. Much of the technical data and site information utilized during the LCA modeling was obtained from the Netherlands’ development framework for offshore wind energy [3], TNO’s offshore wind decommissioning document [8], and the IEA’s 15 MW reference turbine document [9]. Three unique scenarios were modeled for the IJmuiden OWF. The first scenario utilized the technical specifications provided by the Dutch government and TenneT – modeling the IJmuiden OWF with a 25-year operational lifetime. The second scenario increased the operational lifetime to 35 years and adjusted the O&M inputs appropriately. The third scenario sought to understand the impact from improved CRM recycling, based on EU data, and assumed a recycling rate of 56.7%.

The results were reported using the 18 ReCiPe (H) midpoint impact categories and, for the first scenario, showed a 17%

decrease when comparing to the lower bound found by Mendecka and Lombardi [16]. The global warming potential for the three scenarios were quantified: 6.51 g CO_2 eq/kWh for the first scenario, 4.89 g CO_2 eq/kWh for the second scenario, and 6.43 g CO_2 eq/kWh for the third scenario, indicating that the technological developments in the offshore wind industry have continued to lower emissions. In 13 out of the 18 impact categories, the offshore wind turbine was found to be responsible for more than 74% of emissions. This can be primarily attributed to the substantial amount of steel and iron utilized in most parts of the turbine, specifically the support structure – which accounted for 59% of the GWP environmental impacts for the first scenario. As such, it is recommended that wind developers improve material recycling rates and utilize recycled metals to manufacture wind turbine components and infrastructure. According to the IEA, producing metals like steel, aluminum, and copper from recycled scrap is 60 to 90% less energy intensive than primary production using metal ores [18], and would enable the offshore wind industry to further reduce its environmental impacts.

From the analysis, it was determined that improving the operational lifetime of the IJmuiden OWF showed a greater reduction in environmental impacts when compared to improving CRM recycling. This is primarily due to the substantial increase in net total yield, where an additional 90,000 GWh of electricity was produced. However, it was found that the improved CRM recycling scenario showed a decrease of approximately 1% for all impact categories; and a significant decrease of more than 7% in 9 impact categories, with the largest reduction occurring in two impact categories: ionizing radiation at 28% and marine eutrophication at 30%. Although the reduction in metal depletion was greater in the second scenario, it is worth noting that a decrease of around 1% is still significant when considering the substantial quantity of metals and minerals utilized in the construction of the IJmuiden OWF, totaling 624,156 tons, the mass of CRMs accounted for merely 641 tons. Thus, achieving a reduction of approximately 1% in metal depletion, considering the CRMs' 0.1% mass composition, is a noteworthy accomplishment. This reduction demonstrates the potential impact of efficient resource management and highlights the significance and strategic importance of CRMs. This LCA found that the innovations in the offshore wind industry have continued to lower emissions and that electricity production from offshore wind farms will be a key enabler to achieve the ambitious climate goals outlined by the Netherlands and the European Union.

ACKNOWLEDGMENT

I would like to express my sincere gratitude to Guidehouse for providing me with the invaluable opportunity to undertake my master's thesis on a topic that truly ignites my passion. Their support has been instrumental in equipping me with the necessary skills to pursue a fulfilling career in the offshore wind industry. I would also like to extend the thanks to my thesis supervisor, Rik van Rossum, for his guidance and expertise which has been crucial throughout this journey. I would also like to acknowledge the exceptional contributions of other brilliant minds at Guidehouse, namely Lennard Stijtsma, Bob Prinsen, and Sander Meerman.

I am thankful to Cesar Valderrama for his generous assistance in addressing my numerous questions regarding life cycle assessments. His expertise has greatly enriched my understanding of the subject. I am also grateful to my academic advisor, Duarte de Mesquita e Sousa, for his support and guidance.

Furthermore, I would like to express my heartfelt appreciation to my parents, Janis and Johan Svensson, for their unwavering support and encouragement throughout this endeavor. Their belief in my abilities has been a constant source of motivation. Lastly, I extend my gratitude to all the friends I have made along this journey for their companionship and encouragement.

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