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

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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.

Resumo

A indústria eólica offshore continua a desafiar limites com turbinas eólicas de maior capacidade em megawatts (MW). No entanto, os seus impactos ambientais são relativamente desconhecidos devido à falta de informações sobre parques eólicos "offshore" (OWFs), em comparação com os parques "onshore". Nesta dissertação aplicou-se uma metodologia de Avaliação do Ciclo de Vida (ACV) para quantificar e analisar os impactos da produção de eletricidade do OWF de IJmuiden; além disso, esta dissertação contempla o impacto das matérias primas críticas (CRMs) utilizados na indústria eólica "offshore". Os limites do sistema para esta ACV foram definidos na entrega de eletricidade à rede elétrica holandesa e incluíram os recursos, energia, transporte e resíduos associados à instalação, operação e manutenção (O&M), descomissionamento e fim de vida útil (EoL) dos vários componentes do OWF. Três cenários foram modelados: o primeiro cenário modelou o OWF de IJmuiden com base em especificações técnicas de referência, o segundo cenário modelou o OWF com uma vida útil operacional prolongada e o último cenário melhorou a reciclagem de CRMs. Os resultados mostraram que as turbinas eólicas "offshore" são responsáveis por mais de 74% dos impactos ambientais em 13 de um total de 18 categorias de impacto. Os resultados também indicaram que uma melhoria na vida útil operacional de um parque eólico pode reduzir significativamente os impactos ambientais. No terceiro cenário constatou-se que, ao melhorar a reciclagem de CRMs, houve uma redução de aproximadamente 1% em todas as categorias de impacto. Em geral, este estudo constatou que o potencial de aquecimento global devido à produção de eletricidade do OWF de IJmuiden diminui 17% em comparação com o limite inferior encontrado na literatura mais recente.

Palavras-chave: Avaliação do Ciclo de Vida (ACV), Parque Eólico Offshore, Matérias Primas Críticas.

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List of Abbreviations

AC	Alternating Current
AEP	Annual Energy Production
ALO	Agricultural Land Occupation
BOM	Bill of Materials
CFC	Chlorofluorocarbon
CO_2	Carbon Dioxide
CRM	Critical Raw Material
DC	Direct Current
DCB	Dichlorobenzene
DD	Direct-Drive
DDPMG	Direct-Drive Permanent Magnet Generator
EoL	End-of-Life
Eq	Equivalent
EU	European Union
EZK	Netherlands' Ministry of Economic Affairs and Climate
FDP	Fossil Depletion
FEP	Freshwater Eutrophication
FET	Freshwater Ecotoxicity
GHG	Greenhouse Gas
GW	Gigawatt
GWP	Global Warming Potential
HT	Human Toxicity
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IEA	International Energy Association
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile Range
IR	Ionizing Radiation
ISO	International Organization for Standardization
IJVWFZ	IJmuiden Ver Wind Farm Zone
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCoE	Levelized Cost of Energy
kV	Kilovolt
MDP	Metal Depletion

MEP	Marine Eutrophication
MET	Marine Ecotoxicity
MW	Megawatt
NLT	Natural Land Transformation
NMVOC	Non-Methane Volatile Organic Compound
O&M	Operation and Maintenance
ODP	Ozone Depletion
OWF	Offshore Wind Farm
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Formation
RNA	Rotor Nacelle Assembly
RVO	Netherlands Enterprise Agency
SO_2	Sulfur Dioxide
TAP	Terrestrial Acidification
TET	Terrestrial Ecotoxicity
TP	Transition Piece
TSO	Transmission System Operator
U235	Uranium 235
ULO	Urban Land Occupation
USDOE	United States Department of Energy
WDP	Water Depletion
WTG	Wind Turbine Generator
XLPE	Cross-Linked Polyethylene

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has recommended governments and policy makers to utilize life cycle assessments, as they are “a particularly useful methodology for determining total system impacts of a given technology” [1]. An LCA in the scope of wind energy, not only considers the direct emissions from the wind farm’s construction, installation, transport, O&M, decommissioning, and EoL, but also the environmental burdens and resources required throughout the entirety of its lifetime. Furthermore, an LCA can allow for the visualization of the environmental impacts for each of the life cycle stages, providing clarity into the most environmentally impactful features of a wind farm. ***This study aims to assess the environmental impacts of electricity production from the IJmuiden OWF.***

The following section includes information about the offshore wind industry in the Netherlands and elaborates on the country’s future clean energy goals. It includes a background of the intended project site and lays the framework for the LCA. Furthermore, it details the importance of CRMs in the offshore wind industry and explains the connection to the Netherlands’ Responsible Business Conduct framework as well as details the three scenarios modeled.

1.1 Offshore Wind Power in the Netherlands

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. In 2019, offshore wind power accounted for 0.3% of the world’s electricity supply [2] and is expected to grow to around 5.5% by 2050 [3]. 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 [4]. According to the development framework for offshore wind energy, updated June 2022, the Ministry of Economic Affairs and Climate (EZK) has indicated a drive towards a total installed offshore wind capacity of 21 gigawatts (GW) by 2030. This ambitious goal stems from a need to achieve a reduction in carbon dioxide (CO_2) emissions of at least 55% by 2030, compared to 1990 emissions. The Dutch government has made deliberate efforts to enable the industry with the required means to achieve such a reduction by overseeing the construction of the offshore electricity grid [5].

1.2 Background of the IJmuiden Offshore Wind Farm

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 [5]. For the purpose of this LCA the Alpha site was chosen primarily due to the extensive technical data and specifications made available by the Dutch government. Figure 1, on the next page, shows the intended layout of the IJmuiden Ver Alpha and Beta sites.

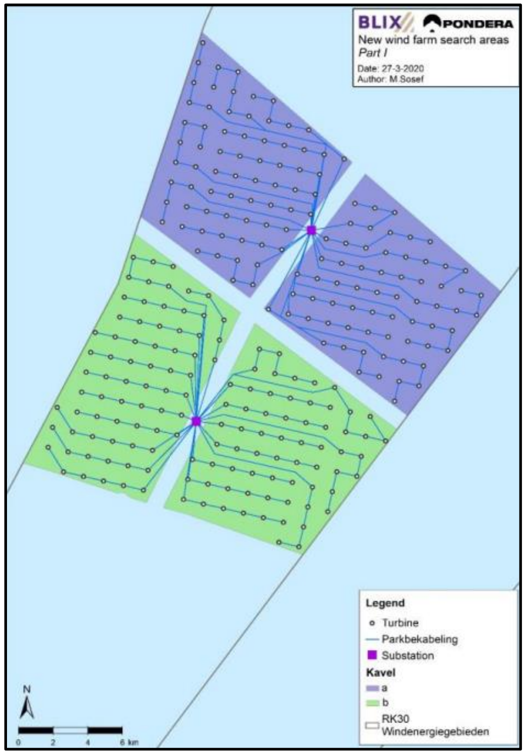

Figure 1: Intended layout of the IJmuiden Ver Alpha and Beta Sites [6]

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 [5]. Technical information regarding wind turbine capacity, rotor diameter, hub height, foundation depth, inter-array cable length, and export cable length was based on assumptions from the most recent literature and expert opinions [6]. The IJmuiden OWF site information can be found in Table 1, below, which includes import parameters such as annual energy product (AEP), transport distances, and rated power. More detailed site information can be found in the later sections of the report.

Table 1: IJmuiden Offshore Wind Farm Site Information

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 (scenario 1)	25	years
Operational Lifetime (scenario 2)	35	years

The Dutch government has assisted in the spatial planning procedures for construction of the offshore grid via the National Coordination Scheme. Additionally, they have provided the grid operator, TenneT, with the financial means to ensure the offshore electricity grid is able to meet the requirements outlined in the development framework for offshore wind energy. TenneT will connect the wind farms as well as construct and manage the offshore grid. This is of notable importance as the timely connection of the wind farms is necessary to prevent yield losses and damage to the wind farms. The technical preconditions and functional specifications listed in the development framework for offshore wind energy played a large role in determining the overall project's design and cost [7]; these preconditions and functional specifications were also evaluated and utilized when determining the assumptions behind the LCA model and inventory analysis. Prior to modeling of the IJmuiden OWF, a comprehensive literature review was performed in order to understand the knowledge gaps, quantify potential sources for LCA input data, and determine the expected range of environmental impacts from previous studies. The literature reviewed further explained the offshore wind industry in the Netherlands and the EU, as well as provided additional information about the IJmuiden OWF, and included a discussion over the importance of CRMs in the EU.

1.3 Critical Raw Materials and Responsible Business Conduct

Additionally, with the significant development of the offshore wind industry in the European Union (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 WTG type [8]. 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. Moreover, in a report by the Joint Research Centre (JRC) two scenarios were analyzed. The first scenario, the low-demand scenario, showed the demand for CRMs necessary to achieve a maximum temperature increase of 2.7 °C. the second scenario, a high-demand scenario, assumed a minor improvement in technology and a 100% global reliance on renewable energy for primary energy production. From the analysis it was determined that the EU mining facilities, which are almost exclusively located in Greenland and Sweden, will be able to provide less than 10% of the global CRM supply, even in the best-case scenario [9]. 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.

Moreover, the Netherlands has begun to implement their RBC framework to promote and guide ethical business practices. RBC refers to the expectation that businesses, both those that operate domestically and internationally, should conduct their operations in a socially conscious and environmentally responsible manner. The Netherlands' RBC framework aims to prevent negative impacts caused by business activities, including human rights violations and environmental degradation [10]. In the scope of the offshore wind industry, the RBC agreements could heavily impact its supply chain – as companies would be mandated to secure their resources, mainly critical minerals, from countries with ethical business practices. As previously mentioned, with the rapid scale-up of the offshore wind industry and the increased demand for CRMs, the offshore wind industry could encounter significant problems sourcing these materials from countries within the EU; this ultimately emphasizes the importance for material reuse and recycling throughout the entirety of the offshore wind industry supply chain.

1.4 Life Cycle Assessment Scenarios

This LCA modeled three separate scenarios 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. The second scenario modeled the OWF with a 35-year operational lifetime and 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.

1.5 Thesis Structure

The structure of this master's thesis, titled: A Life Cycle Assessment of Electricity Production from the IJmuiden Offshore Wind Farm, is as follows. The first section, *introduction*, outlines the background of the offshore wind industry in the Netherlands, setting the tone and introducing the need for further clarity in regard to the emissions from offshore wind electricity production; additionally, it introduces the Netherlands' RBC framework and the three scenarios modeled as a part of this LCA. The second section, *literature review*, provides a detailed background of the offshore wind industry in the EU and further information about the IJmuiden project site, as well as explains the importance of CRMs in the scope of the Netherlands' RBC framework; additionally, it explains the three objectives of the literature review – which were to identify relevant sources of data for the offshore wind farm, quantify the range of environmental impacts from previous offshore wind LCAs, and identify knowledge gaps. The third section, *methodology*, details the methodology utilized when performing the LCA; the methodology follows the International Organization for Standardization (ISO) standards 14040 and 14044, ensuring accuracy and reproducibility throughout the project. The fourth section, *inventory analysis*, contains a comprehensive inventory, compiled from a variety of sources, for the IJmuiden OWF – including the input data for the raw material extraction, refining, and transport; manufacture and assembly of components; O&M, and EoL. The fifth section, *results and analysis*, contains the comprehensive environmental impact results from producing electricity from the IJmuiden OWF, provides a detailed analysis of the climate change impacts and metal depletion, as well as discusses, in detail, the environmental impacts from the offshore wind turbine for all three cases. The final section, *conclusion*, summarizes the pertinent findings from the IJmuiden OWF LCA and provides recommendations for areas of further work.

2. Literature Review

The following literature review includes an explanation of the offshore wind industry in the Netherlands and the EU, as well as information pertaining to the IJmuiden OWF, and a discussion over the importance of CRMs in the EU. Most of the background information of the offshore wind industry came from the IEA's offshore wind outlook from 2019 [2]; and CRM information from the EU's Critical Raw Materials Act [11].

Many of the existing LCAs of OWFs have only sought to analyze the environmental impacts from the WTG. However, this report sought to model the entirety of an offshore wind farm including the wind turbines and grid connection. Additionally, this literature review was performed with three objectives in mind. The first objective was to determine sources of pertinent information pertaining to offshore wind systems; more specifically, the detailed material composition for various wind farm components, which would serve as a foundation for the LCA. The second objective was to quantify the range of environmental impacts from offshore wind electricity production. The final objective was to identify areas of further work from previous LCAs in the offshore wind industry.

2.1 Overview of the Offshore Wind Industry

According to the IEA, offshore wind power capacity is set to increase more than 15 times over the next two decades, turning it into a $1 trillion business. However, its potential is far greater than that, and is predicted to be the key for decarbonization as well as the leading source of electricity generation in Europe. The offshore wind industry will also enable hydrogen utilization in hard-to-abate sectors like iron & steel, and transportation [2].

In 2019, offshore wind power had a total capacity of 23 GW, with more than 80% coming from European waters. However, it only accounts for 0.3% of the global electricity supply. The industry has been experiencing rapid growth in the last few decades, with a growth rate of nearly 30% per year between 2010 and 2018 [2]. This rapid growth can be explained by the following reasons: technological improvements in the offshore wind industry have enabled OWFs with higher rated capacities and reduced O&M requirements, and the supply chain has become more streamlined, with turbine manufacturers developing large-scale manufacturing sites and governments improving the tender process for wind farm developers. One such example can be found in the Netherlands, in 2013 the government formed a broad coalition of employers' associations, trade unions, environmental protection organizations, and energy companies and created the Energy Agreement for Sustainable Growth; in regard to wind energy, the agreement committed the government to assign and develop three offshore wind zones – Borssele, Hollandse Kust zuid (Dutch Coast south), and Hollandse Kust noord (Dutch Coast north). All of which were situated in the Dutch region of the North Sea and have increased the offshore wind capacity of the Netherlands by 3.5 GW. In recent years, the Netherlands revised the existing climate agreement to form a more encompassing one, which is still in place today, and included the addition of the Hollandse Kust west (Dutch Coast west), Ten Noorden van Wadden (North of the Wadden Sea Islands), and the IJmuiden Ver – which is the focus of this report [12].

Today, the Netherlands is an industry leader in the offshore wind sector. The Dutch government has set ambitious climate goals and aims to achieve a reduction in CO_2 emissions of at least 55% by 2030; moreover, in their climate agreements, they are committing to install an additional 7 GW of offshore wind capacity in the North Sea between 2023 and 2030. Where, by 2030, offshore wind electricity will comprise approximately 40% of the Netherland's current electricity consumption [12].

2.2 Technical Information about the IJmuiden Offshore Wind Farm

From the development framework for offshore wind energy, much of the pertinent information about the IJmuiden OWF was found. The framework contained information about the location of the OWF, its expected commissioning date, the expected service life, the maximum capacity, the minimum transmission capacity, method of electrical connection, planned delivery dates for OWF components, and future offshore wind developments considered when taking into account the method of electrical connection. The IJmuiden OWF is a part of the IJVWFZ and is the fourth of eight sites being tendered as a part of the development framework for offshore wind energy. It will have an approximate capacity of 6 GW, with sub-sites Alpha, Beta, and Gamma comprising 2 GW each. IJmuiden Ver sub-site Alpha was the intended focus area for this LCA and will be referred to as the IJmuiden OWF for the entirety of this report.

The offshore wind turbines of the IJmuiden OWF were specified as 134 15 MW turbines which would be connected by 66 kV inter-array cabling; the inter-array cables would connect the turbines to the offshore converter station and then be transmitted to the onshore substation through 525 kV HVDC export cabling. The IJmuiden OWF utilizes HVDC transmission due to its substantial distance to shore, approximately 150 km from the offshore converter station to the onshore substation. The offshore converter station is a part of TenneT's 2 GW program, which seeks to standardize new offshore wind substation installations [13]. Moreover, HVDC transmission is a relatively new development in the offshore wind industry, as the average distance to shore was found to be 41 km for the OWFs reviewed in Díaz and Guedes Soares [14]. According to Zhengxuan et al., 2020, HVDC transmission becomes economically viable when transport distances are in the range of 150 to 200 km for wind farms with a capacity of 400 to 500 MW [15]; and since the capacity of the IJmuiden OWF is substantially over this range, HVDC transmission becomes the clear solution.

Further information about the IJmuiden OWF site was obtained from a report from BLIX Consultancy B.V., in partnership with Pondera, Energy Solutions, KCI, and TenneT; performed for EZK to quantify the LCoE of the various OWF sites in the Netherlands [6]. This report provided technical information about the IJmuiden OWF's AEP, which was based on 15 years of long-term mesoscale data from the KNMI North Sea Wind Atlas and validated against publicly available wind measurements. The long-term average annual wind speed at 140 m height was determined to be 10.2 m/s with a Weibull scale parameter (A) of 11.46, and a Weibull shape parameter (k) of 2.182. Additionally, the total inter-array cable distance and foundation depth were specified, at 236.5 km and 28 m, which were based on soil conditions in the North Sea. Finally, the net AEP was quantified at 8973 GWh/year.

2.3 Importance of Critical Raw Materials

As mentioned in the introduction, CRMs are an indispensable commodity necessary to achieve the clean energy transition. CRMs are required in a variety of strategic sectors, including the net zero industry, digital industry, aerospace, and defense sectors. Currently, the EU depends heavily on imports, often from quasi-monopolistic third country suppliers [11], such as China for neodymium and dysprosium, and Brazil for niobium [16] – which are the focus of this LCA. These countries have highly concentrated market control and limited competition which could induce the potential for market power abuse. The EU has decided to mitigate the supply chain risks associated with such strategic dependencies with the goal of enhancing their economic resilience. One such example of economic instability can be seen following the energy crisis created after Russia's invasion of Ukraine. The EU has laid out clear and achievable goals in the Critical Raw Materials Act to improve their ability to diversify and enhance the resilience of the CRM supply chain [11].

Moreover, considering the Netherlands' RBC framework, on a country-level, additional emphasis has been placed on businesses to conduct their practices in an ethical and environmentally conscious manner. The RBC framework requires businesses, both those that operate domestically or internationally, to mitigate human rights violations and environmental degradation [10]. In the scope of the offshore wind industry, the RBC agreements could heavily impact its supply chain – as companies would be mandated to secure their resources, mainly CRMs and metals, from countries with ethical business practices. Take for example China's BYD, which is one of the world's largest suppliers of lithium-ion batteries. In May of 2016, toxic chemical leaching caused by the Ganzizhou Rongda lithium mine resulted in the death of fish and animals found in and along the Liqi River. This disaster was the third incident in seven years, primarily due to the increased demand of lithium demanded for the clean energy transition. Additionally, between 2016 and 2018 lithium prices doubled due to exponentially increasing demand [17]. For these reasons, it is clear why the EU and the Netherlands have implemented legislation and frameworks to diversify and enhance the ethical supply of these strategic commodities; and explains the necessity of the improved CRM recycling scenario as a part of the LCA.

2.4 Objectives

The three most influential sources of information for the IJmuiden OWF will be discussed further in this section of the report. Most of the relevant information utilized for the modeling of the IJmuiden OWF was obtained from TNO's offshore wind decommissioning document [18], an excel tool obtained from Kouloumpis and Azapagic [19], and IEA's technical report on the definition of a 15 MW offshore wind turbine [20]. TNO's offshore wind decommissioning document provided most of the technical data on masses for the wind turbine components, as well as included formulas for determining the mass of individual components based on the rated capacity of the wind turbine or site characteristics. The excel tool, from Kouloumpis and Azapagic, was created with the goal to enable designers, developers, and policy makers to customize the inputs for a specific offshore wind farm configuration and quickly estimate the impacts; and provided the percentage mass contribution and energy requirements required for the various OWF components [19]. Lastly, the reference turbine from the IEA served as a pivotal reference for this life cycle assessment, many of the values obtained from other sources were cross-referenced with the IEA reference turbine to improve accuracy throughout the modeling process. Furthermore, as explained by the IEA, reference wind turbines serve multiple roles within the wind community; they serve as open benchmarks and provide transparency within the industry [20].

The possible range of environmental impacts from offshore wind energy was obtained from Dolan and Heath [7], Kadiyala et al. [21], and Mendecka and Lombardi [22]. Dolan and Heath performed a comprehensive review of life cycle assessments for wind energy and systematically evaluated 240 utility-scale wind installations. As a part of the review, Dolan and Heath applied a rigorous methodology to consolidate 49 references which met the minimum requirements for quality, transparency, and relevance, as well as excluded any outliers which did not meet these requirements. From this, they were able to quantify the global warming potential (GWP) from 7.2 – 23 g CO_2 eq/kWh for offshore wind farms. Kadiyala et al. found a similar range for offshore wind energy, ranging from 3.2 – 24 g CO_2 eq/kWh [21]. However, the lower value of 3.2 g CO_2 eq/kWh was not comparable to other LCAs for offshore wind energy as it corresponded to a deep floating offshore wind turbine. The most recent study, from Mendecka and Lombardi, further adjusted the ranges to 7.8 – 32 g CO_2 eq/kWh, incorporating additional studies [22].

Regarding the third objective, most of the existing literature pertaining to life cycle modeling of OWFs had wind turbines with a rated capacity ranging from 2 to 3 MW, with only a few studies in the 5 to 6 MW range; little to no studies pertaining to offshore wind turbines with rated capacities above 10 MW were found as a part of this literature review. This is notable, as it is expected that the technological developments and increased AEP of larger wind turbines could potentially lead to significantly reduced environmental impacts.

Additionally, 80 out of 107 LCAs analyzed by Dolan and Heath reported a wind farm lifetime of 20 years [7], which, when compared to the 25-year lifetime of the IJmuiden OWF, could lead to higher environmental impacts. For most of the previous LCAs pertaining to offshore wind energy, the environmental impacts from scour protection, which is necessary to stabilize the seabed and protect the offshore wind turbine foundation, was not considered; the total quantity of scour protection required for large 15 MW turbines was obtained from a confidential source specializing in the foundation design of offshore turbines and totaled nearly 5,000 tons per turbine, the performed LCA sought to model and understand the environmental impacts from the substantial quantity of scour protection required for the IJmuiden OWF. Moreover, the literature review indicated that the availability of information pertaining to the life cycle assessment of offshore wind farms is still in its relative infancy, as most LCAs have been focused on onshore wind farms [22]. However, this LCA sought to provide a more detailed account of the environmental impacts from offshore wind electricity production, as the offshore wind industry is experiencing exponential growth [2]. As such, the need to quantify the environmental impacts from GW scale offshore wind power generation is more important than ever before.

3. 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 (ILCD) 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 [23]. In accordance with these standards, this LCA was performed in four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. The results and analysis are reported in their own section later in the report.

The following section outlines the goal, scope, and system boundaries for the performed LCA. The primary goal of this LCA was to quantify the life cycle environmental impacts of electricity production from the IJmuiden OWF in the Netherlands. 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. Another aim of the LCA was to understand the impact of CRMs in the offshore wind industry – as it is forecasted that the demand will increase significantly in the coming years. An overview of the system boundaries can be seen in Figure 2, below.

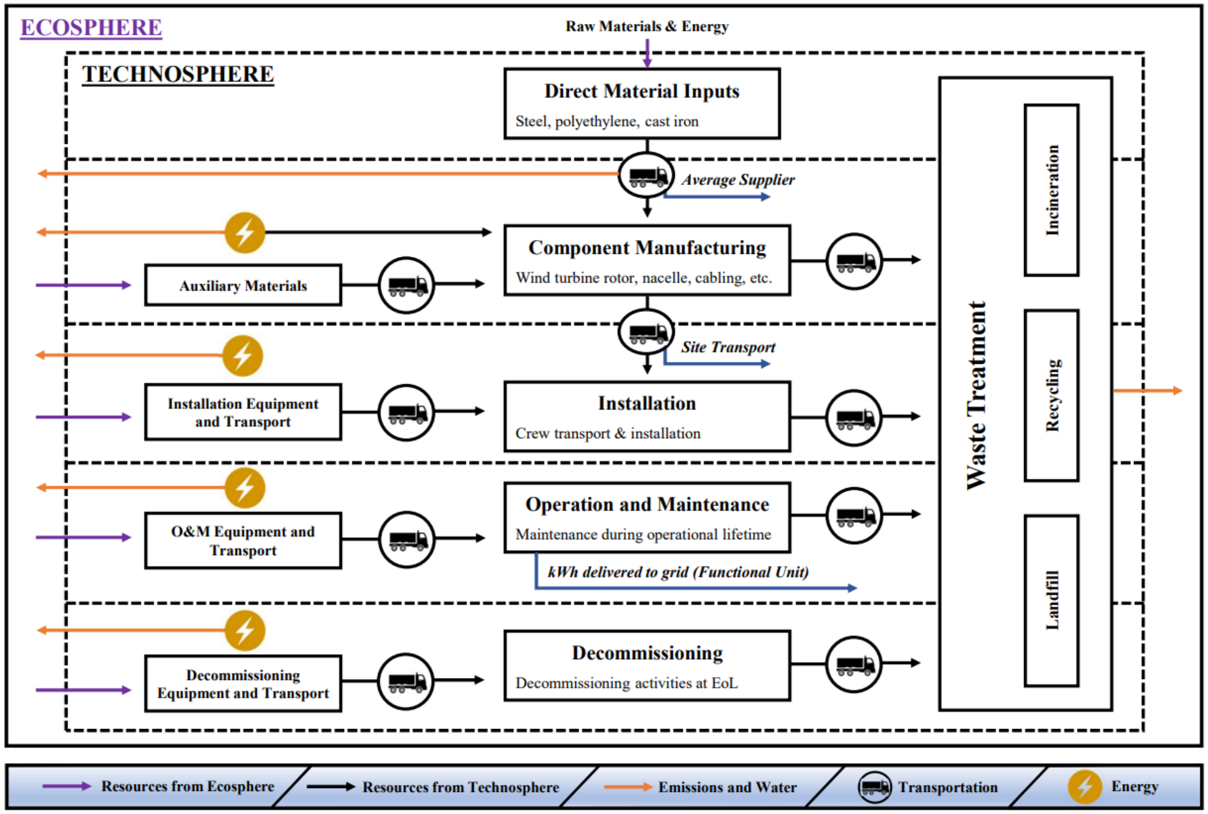

Figure 2: System Boundaries for the IJmuiden Offshore Wind Farm

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.

The OpenLCA software was selected to perform the impact assessment and the ReCiPe midpoint impact assessment method was utilized. Midpoint impact assessment allows for further transparency of the reported results due to the breakdown of multiple characterization factors. On the other hand, endpoint impact assessment methods provide a simplified approach to characterization factor reporting but are far less common in wind energy LCA modeling [22]. Endpoint assessments are known to be far less accurate since causal links between emissions and impacts are weaker [8]. Table 2, below, shows the life cycle impact assessment (LCIA) categories, acronyms, and associated units.

Table 2: ReCiPe (H) Midpoint Impact Categories

	Impact Category	Acronym	Unit
1	Particulate Matter Formation	PMF	g PM10 eq
2	Human Toxicity	HT	g 1.4 DCB eq
3	Ionizing Radiation	IR	g U235 eq
4	Fossil Depletion	FDP	g oil eq
5	Freshwater Eutrophication	FEP	g P eq
6	Ozone Depletion	ODP	g CFC 11 eq
7	Natural Land Transformation	NLT	m^2
8	Climate Change	GWP	g CO_2 eq
9	Marine Eutrophication	MEP	g N eq
10	Agricultural Land Occupation	ALO	m^2
11	Metal Depletion	MDP	g Fe eq
12	Water Depletion	WDP	m^3
13	Marine Ecotoxicity	MET	g 1.4 DCB eq
14	Freshwater Ecotoxicity	FET	g 1.4 DCB eq
15	Photochemical Oxidant Formation	POF	g NMVOC
16	Terrestrial Acidification	TAP	g SO_2 eq
17	Urban Land Occupation	ULO	m^2
18	Terrestrial Ecotoxicity	TET	g 1.4 DCB eq

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.

4. 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 critical minerals, 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 reason for selecting a DD wind turbine will be discussed in detail in section 4.1.2.2.2.

The following section will detail the life cycle inventory (LCI). Attributional modeling was utilized, which depicts the environmental impacts that can be attributed to a system over its life cycle. Attributional modeling uses historical, fact-based, measurable data of known uncertainty and incorporates all the processes that are identified to relevantly contribute to the system being studied.

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 LCI such as number of turbines, transmission distances, and size of the offshore substation was provided by the Dutch government’s development framework for offshore wind energy [5] and TenneT’s consultation for a 2 GW HVDC offshore grid connection system [13]. Valuable information about the decommissioning and structural mass of a 15 MW DD wind turbine was collected from van der Meulen et al. [18], and the IEA’s 15 MW reference turbine document [20]. The following figure shows the IJmuiden OWF input tree.

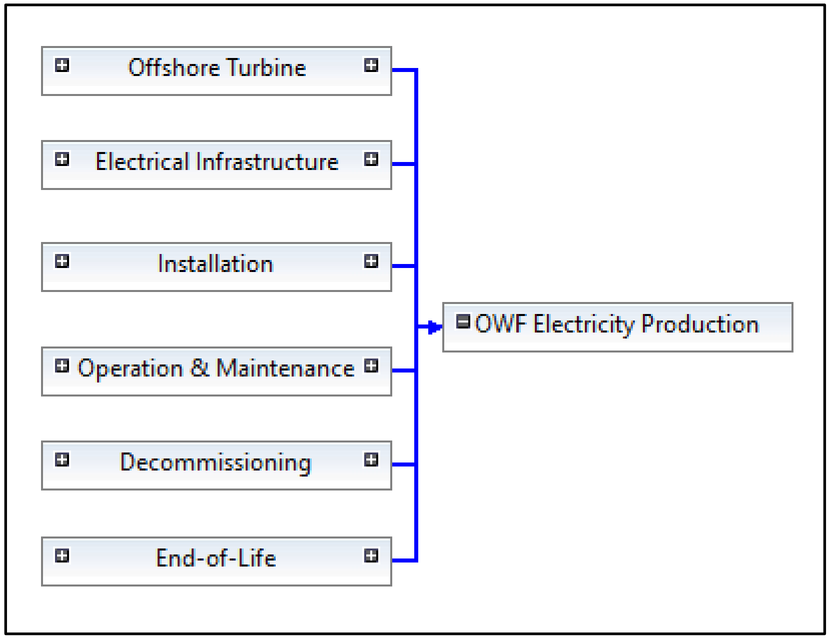

Figure 3: IJmuiden Offshore Wind Farm Input Tree

4.1 Offshore Turbine

For the IJmuiden OWF 134 15 MW DD offshore wind turbines were specified to meet the 2 GW capacity outlined in the development framework for offshore wind energy [6, 5]. The offshore turbine consisted of the support structure, which includes the tower, transition piece (TP), foundation, and scour protection; and the rotor nacelle assembly (RNA), which includes the rotor and nacelle. The IEA 15 MW reference turbine was heavily consulted when sourcing necessary information for the life cycle assessment [20]. A diagram of the offshore turbine input tree can be seen in the following figure.

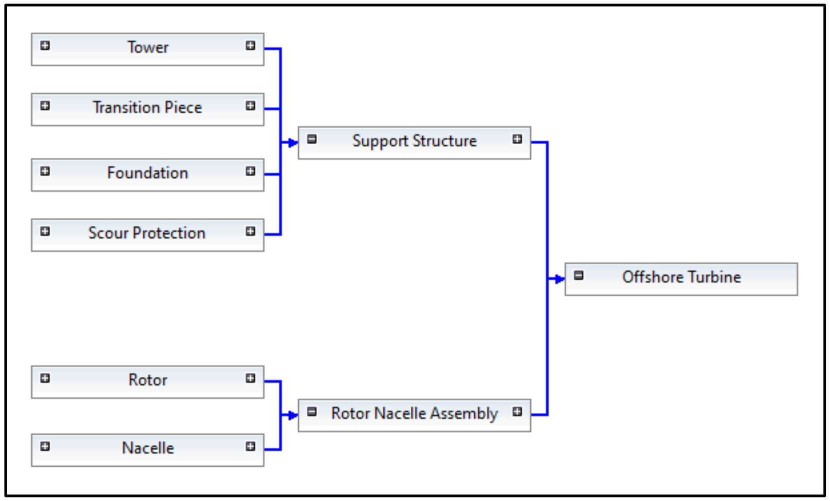

Figure 4: Offshore Turbine Input Tree

4.1.1 Support Structure

Four distinct components were modeled for the support structure; the support structure was modeled as a fixed-bottom monopile with tower, TP, monopile, and scour protection. The TP connects the monopile to the tower; it should be noted that industry leaders are trying to shift towards a transition piece-less monopile, however, since this technology is not common practice in the offshore wind industry, the offshore turbines of the IJmuiden OWF were modeled with a TP. The monopile foundation was selected for the IJmuiden offshore wind farm for several reasons, including its low manufacturing, installation, and transport costs, as well as low risk profile [24]. This type of foundation is the most common worldwide, constituting more than 81% of offshore wind turbines in European waters [25], and particularly suitable for shallow water applications – which represents the vast majority of the North Sea. Figure 5, on the next page, shows a diagram of the monopile support structure for an offshore wind turbine [26].

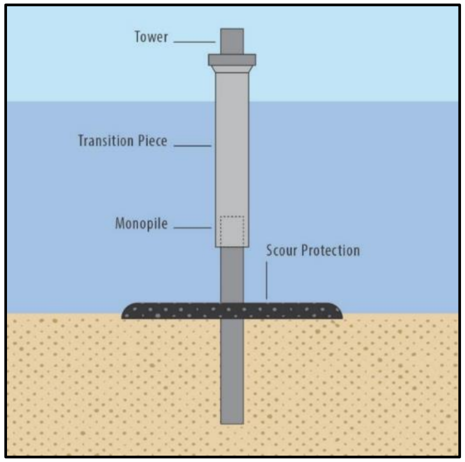

Figure 5: Monopile Support Structure Diagram [26]

4.1.1.1 Tower

Van Oord, a Dutch maritime contractor who specializes in the installation of monopiles and towers, secured the contract for the installation of steel monopiles and towers for the Borssele III & IV offshore wind farms [27]. The extra-long monopiles utilized for this application were manufactured by the Sif Group at their monopile manufacturing site in Rotterdam. The Sif Group also was selected as the main supplier for the Hollandse Kust Noord offshore wind farm [28]. For these reasons, it was assumed that both the towers and monopiles for the IJmuiden OWF would also be manufactured in Rotterdam, which is approximately 150 km from the project site. The material inputs for the steel tower and tower internals were based on the polynomial trend [29] for tower mass based on hub height, and its mass was quantified at 805 tons. The associated hub height was taken from the IEA 15 MW reference turbine and specified at 140 m [20]. The percentage mass contribution of the tower's material inputs can be seen in Table 3. In the supplement information a complete list of material inputs, including energy use, waste, and transportation, can be found.

Table 3: Tower Percentage Mass Contribution

Input	Contribution
Steel, Low-Alloyed	98.20%
Aluminum	1.80%

4.1.1.2 Transition Piece

Tata Steel secured the contract to produce the TPs for the Dogger Bank OWF, which is the largest OWF to date and is located in the North Sea [30]. It was assumed that the TP would be manufactured at Tata Steels' manufacturing plant in Whales. The approximate transportation distance from their port in Whales to the IJmuiden project site was determined to be 1,250 km. Material inputs for the TP were based on TNO's offshore wind farm decommissioning document, with an overall mass ranging from 300 to 500 tons [18]. The larger bound of 500 tons was selected for the IJmuiden project site due to the utilization of large MW wind turbines. The percentage mass contribution of the TP's material inputs can be found in Table 4, on the following page.

Table 4: Transition Piece Percentage Mass Contribution

Input	Contribution
Steel, Low-Alloyed	97.20%
Silica Sand	1.50%
Cement	1.30%

4.1.1.3 Foundation

As mentioned in section 4.1.1.1, it was assumed that the monopile foundation would be manufactured in Rotterdam [28]. Like the transition piece, the overall mass for the foundation was taken from TNO's offshore wind decommissioning document, specified in the range of 800 to 2,000 tons [18]. To accommodate the larger WTG and significant tower height, the more conservative value of 2,000 tons was utilized. The foundation material composition was based on Kouloumpis and Azapagic, 2021 [19]. The percentage mass contribution of the foundation's material inputs can be found in Table 5.

Table 5: Foundation Percentage Mass Contribution

Input	Contribution
Steel, Low-Alloyed	97.20%
Silica Sand	1.50%
Cement	1.30%

4.1.1.4 Scour Protection

One important design feature of a wind turbine, which has not seen much attention in previous life cycle assessments, is scour protection. Scour is the phenomenon that causes the loss of topsoil or sediment around the foundation of offshore structures; scour can represent a significant concern for offshore wind turbines, as it can undermine the structure's stability. In some cases, compromising a structure's load-bearing capacity and potentially lead to collapse [31]. The Figure 6, on the next page, shows the scour effect on a wind turbine foundation.

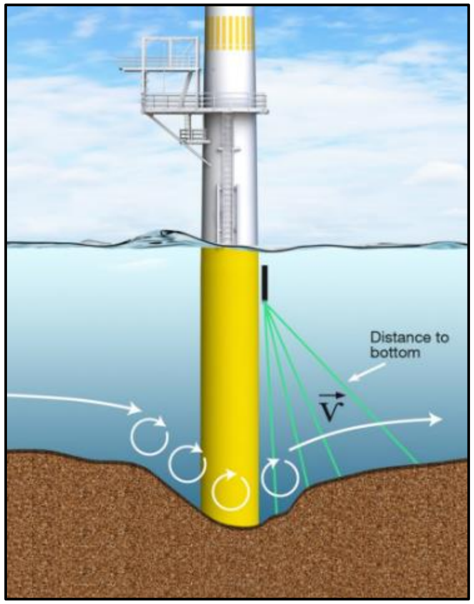

Figure 6: Scour Phenomenon on an Offshore Wind Turbine [32]

Scour protection consists of dumping large quantities of crushed rock around the foundation of a wind turbine, over a geotextile layer, to avoid the deterioration of the seabed. In the case of larger offshore 15 MW turbines the quantity of stone is increased substantially. The total amount of scour protection required for a 15 MW turbine was obtained from a confidential source specializing in the foundation design of offshore structures and quantified at 4,900 tons. The percentage mass contribution of the scour protection's material inputs can be seen in Table 6, below.

Table 6: Scour Protection Percentage Mass Contribution

Input	Contribution
Gravel	99.99%
Geotextile	0.01%

4.1.2 Rotor Nacelle Assembly

The RNA of a wind turbine refers to the structure which contains the moving parts and operating components of the turbine; the overall mass for the RNA was quantified at 1,070 tons [18]. The rotor consists of the wind turbine blades and hub, as well as the nacelle, which contains a variety of subcomponents and is dependent on the WTG type. In the case of the IJmuiden OWF, the DDPMG was selected and modeled, as this is the trend in the offshore wind industry [3]. DDPMGs require far less maintenance, because of the lack of gearbox, which becomes increasingly enticing as OWFs continue to move further offshore. The rotor and nacelle will be discussed in further detail in the following sections. Figure 7, on the next page, shows the RNA input tree.

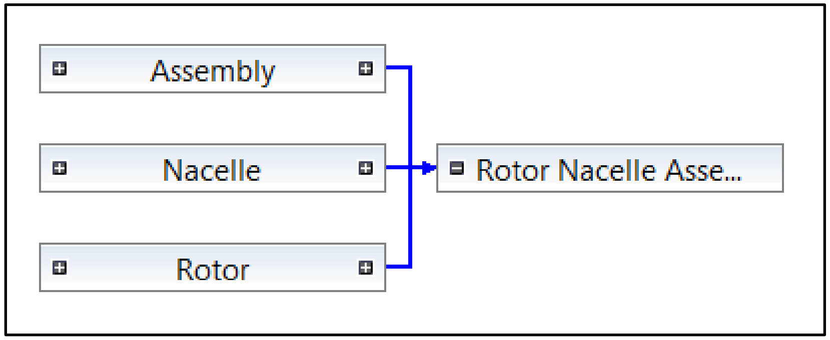

Figure 7: Rotor Nacelle Assembly Input Tree

4.1.2.1 Rotor

As previously mentioned, the rotor consists of the wind turbine blades and hub. The mass of the rotor components was found to increase linearly with turbine capacity [18] and taken from NREL's IEA 15 MW offshore reference turbine at approximately 423 tons [20]. These values were then cross referenced with data from other sources and found to be in similar ranges [33]. An overview of the rotor inputs can be seen in Figure 8 below.

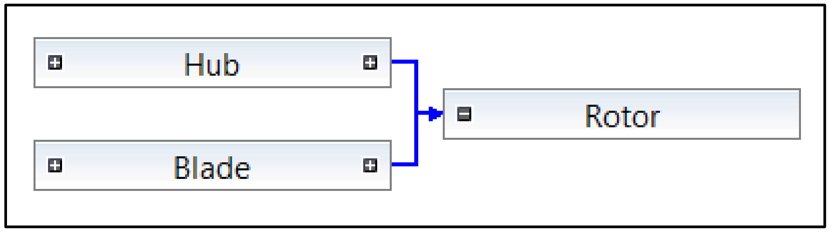

Figure 8: Rotor Input Tree

4.1.2.1.1 Blade

Wind turbine blades are comprised of a combination of composite materials, including epoxy resin, glass fiber reinforced plastic, lightweight wood, and polypropylene. The overall mass for the wind turbine blades was specified in the IEA 15 MW reference turbine document at 195.75 tons, with an individual blade mass of 65.25 tons [20]. The percentage mass contribution of the blade's material inputs was taken from Kouloumpis and Azapagic, 2021 [19], and can be found in the following table.

Table 7: Blade Percentage Mass Contribution

Input	Contribution
Glass Fiber Reinforced Plastic	66.80%
Epoxy Resin	26.40%
Paraná pine	4.90%
Polypropylene	1.90%

4.1.2.1.2 Hub

From Meulen et al., 2021, the hub mass was found to increase linearly with turbine capacity [18] and was quantified at 227.25 tons for a 15 MW turbine. The percentage mass contribution of the hub's material inputs can be found in the following table [19].

Table 8: Hub Percentage Mass Contribution

Input	Contribution
Cast Iron	46.10%
Chromium Steel	26.90%
Steel, Low-Alloyed	24.20%
Glass Fiber Reinforced Plastic	2.80%

4.1.2.2 Nacelle

The nacelle consists of the nacelle cover, DDPMG, base plate, DD shaft, and yaw mechanism. While there are many other components present in the nacelle, these components constitute most of the nacelle mass. The following subsections will discuss, in detail, the material inputs required for each of the nacelle components. Figure 9, below, depicts the nacelle input tree.

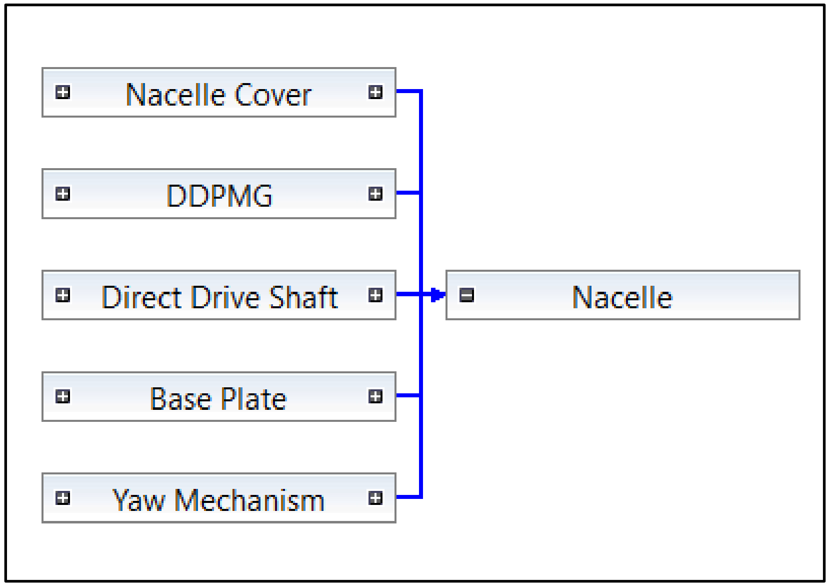

Figure 9: Nacelle Input Tree

4.1.2.2.1 Nacelle Cover

The nacelle cover consists of epoxy resin, glass fiber reinforced plastic, and chromium steel; the percentage mass contribution of the material inputs was derived from Kouloumpis and Azapagic, 2021, and can be found Table 9 on the next page. The overall mass was quantified at 36.36 tons [29].

Table 9: Nacelle Cover Percentage Mass Contribution

Input	Contribution
Glass Fiber Reinforced Plastic	49.51%
Epoxy Resin	33.00%
Chromium Steel	17.49%

4.1.2.2.2 Direct-Drive Permanent Magnet Generator

The overall generator mass was scaled accordingly from TNO's offshore wind decommissioning document and was found to largely depend on the WTG type utilized. For offshore applications, wind turbine developers are pursuing DDPMGs because of their reduced maintenance concerns and reliability. Figure 10 shows a direct-drive offshore wind turbine [34].

Direct-drive turbines simplify nacelle systems and can increase efficiency and reliability by avoiding gearbox issues. They work by connecting the rotor directly to the generator to generate electricity.

Figure 10: Direct-Drive Offshore Wind Turbine [34]

In TNO’s document, two key formulas were utilized in order to determine the associated generator and magnet masses [18]. Table 10 shows the percentage mass contribution of the material inputs for the DDPMG.

Table 10: DDPMG Percentage Mass Contribution

Input	Contribution
Cast Iron	94.09%
Copper	3.17%
Soft Iron	1.82%
Neodymium Oxide	0.84%
Boron	0.03%
Dysprosium	0.03%
Ferroniobium	0.02%
Aluminum	0.01%

4.1.2.2.3 Direct-Drive Shaft

The DD shaft was modeled as 100% chromium steel, and its overall mass was quantified at 15.75 tons. This overall mass was determined from TNO’s offshore wind decommissioning document and found to have a relationship of 1.05 tons per megawatt [18]. The following table shows the percentage mass contribution of the material inputs for the DD shaft.

Table 11: Direct-Drive Shaft Percentage Mass Contribution

Input	Contribution
Chromium Steel	100%

4.1.2.2.4 Base Plate

The base plate was modeled as 100% cast iron, with an overall mass of 75 tons. The base plate mass was found to have a linear relationship with the turbine capacity at a mass of 5 tons per megawatt [18]. Table 12, shows the percentage mass contribution for the base plate's material inputs. Additional information about processing requirements for the base plate can be found in the supplemental information.

Table 12: Base Plate Percentage Mass Contribution

Input	Contribution
Cast Iron	100%

4.1.2.2.5 Yaw Mechanism

As with the DD shaft and base plate, the yaw mechanism's overall mass was found to have a linear relationship with turbine rated capacity. The mass was quantified at 73.95 tons, with a relationship of 4.93 tons per megawatt. The material composition for the yaw mechanism was found to have equal parts cast iron and copper, with an additional small fraction of chromium steel. Table 13, below, shows the material inputs and percentage mass contribution for the yaw mechanism.

Table 13: Yaw Mechanism Percentage Mass Contribution

Input	Contribution
Cast Iron	49.28%
Copper	49.28%
Chromium Steel	1.44%

4.2 Electrical Infrastructure

TenneT, the Netherlands' transmission system operator (TSO), controls and operates the electrical infrastructure necessary for the deployment of offshore wind energy in the North Sea. As outlined in the development framework for offshore wind energy, EZK has tasked TenneT to enable wind farm developers with the necessary means for grid interconnection. TenneT will supply new offshore wind farms with HVDC connections to meet the required transmission capacity, 2 GW per connection [35]. This new 2 GW grid connection has been specified as the new standard in the Netherlands and was modeled accordingly as a part of this life cycle assessment.

The following section outlines the electrical infrastructure necessary to enable power production from the IJmuiden OWF. The electrical infrastructure included the 66 kV inter-array cabling, 525 kV Cross-Linked Polyethylene (XLPE) export cabling, offshore converter station, and onshore substation. Figure 11, on the next page, shows the electrical infrastructure input tree.

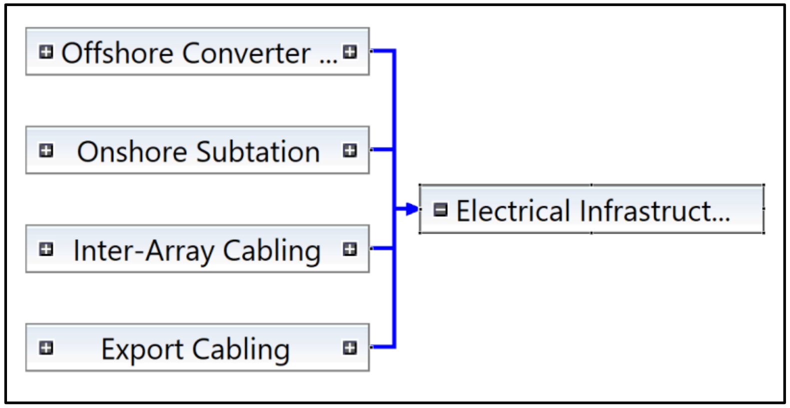

Figure 11: Electrical Infrastructure Input Tree

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. Figure 12, below, depicts TenneT's HVDC grid connection concept [13].

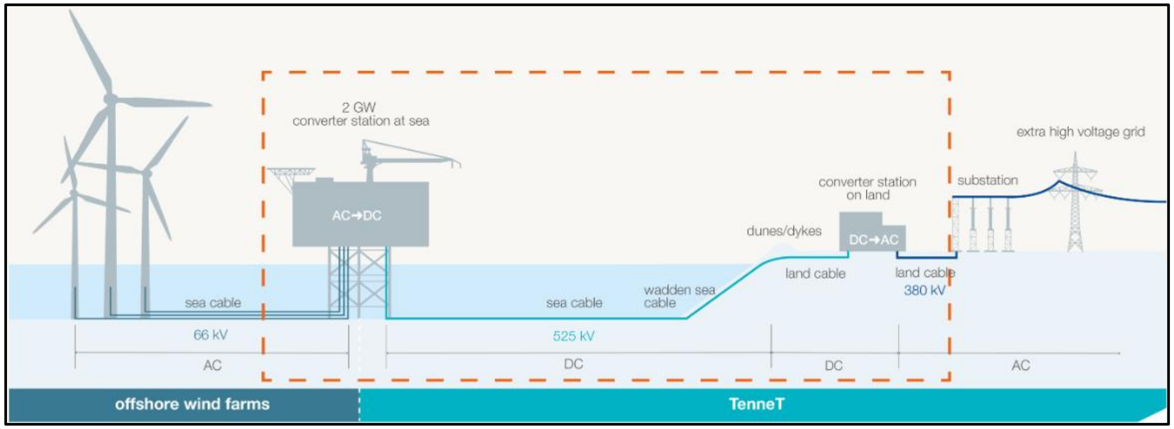

Figure 12: TenneT's HVDC Grid Connection Concept [13]

4.2.1 Substations

Substations are a critical component of an offshore wind farm; they house the electrical high-voltage and medium-voltage components necessary for transforming power. Substations also provide monitoring and control capabilities, manage reactive power, and enable planned and unplanned maintenance activities. As previously mentioned, TenneT will construct and maintain both the HVDC offshore converter station and onshore substation. The transport distance between the offshore converter station and the onshore substation was found to be approximately 150 km, which presents the perfect opportunity for HVDC transmission. According to Zhengxuan et al., 2020, HVDC transmission becomes viable when transport distances are in the range of 150 to 200 km for wind farms with a capacity of 400 to 500 MW [15]. As is the case for the IJmuiden OWF, with a capacity of 2 GW, HVDC transmission becomes the clear solution.

The material inputs for the offshore converter station and onshore substation were taken from [36] and scaled linearly based on the individual percentage mass increase for the offshore converter station and onshore substation. The following table shows the stations' material inputs and percentage mass contribution. Additionally, a more detailed inventory including energy requirements and material processing can be found in the supplemental information.

Table 14: Substation Percentage Mass Contribution

Input	Contribution
Steel, Low-Alloyed	68.41%
Gravel	27.69%
Lubricating Oil	1.28%
Sand	0.96%
Copper	0.70%
Aluminum	0.52%
Sulfate Pulp	0.14%
Epoxy	0.12%
Structural Timber	0.07%
Glass Fiber Reinforced Plastic	0.03%
Sulfur Hexafluoride	0.03%
Chromium Steel	0.02%
Cast Iron	0.01%

4.2.2 66 kV Inter-Array Cabling

TenneT selected NKT and Prysmian to manufacture the 66 kV inter-array and 525 kV export cables for the IJmuiden OWF [37]. The total inter-array cable distance was quantified at 236.5 km [6], and transportation distances were averaged between the different manufacturing sites. Table 15, below, shows the percentage mass contribution of the material inputs for the inter-array cabling.

Table 15: Inter-Array Cabling Percentage Mass Contribution

Input	Contribution
Steel, Low-Alloyed	41.38%
Lead	27.59%
Copper	20.69%
Polyethylene	6.90%
Polypropylene	3.45%

4.2.3 525 kV Export Cabling

As specified in the development framework, the offshore converter station and onshore substation will be connected by a 525 kV XLPE export cable bundle; the bundle consists of two single core 525 kV HVDC cables, a metallic return cable, and a fiber optic cable. This type of cable bundle was chosen to ensure maximum availability from the OWF, in the event of a cable outage one of the single core 525 kV cables could supply power while the other cable underwent repairs [5]. Since a bill of materials was not provided, literature was utilized in order to quantify the material inputs for the single core HVDC cables. Two main pieces of literature, ABB's XLPE submarine cable systems document [38] and a previous life cycle assessment of fiber optic cables [33], were primarily consulted when quantifying the necessary material inputs for the IJmuiden OWF. Figure 13, below, shows the export cabling input tree. A comprehensive list of material and energy inputs can be found in the supplemental information of this report.

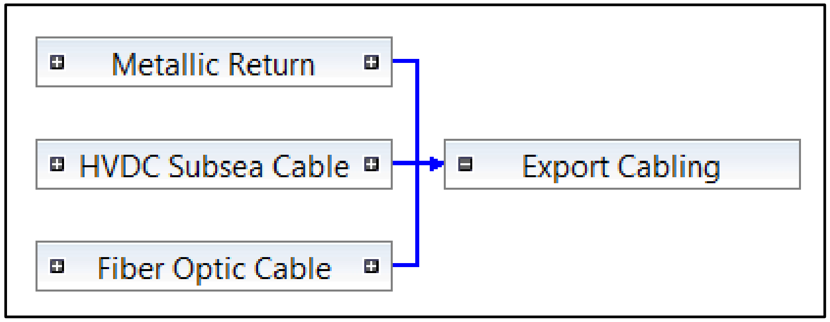

Figure 13: Export Cabling Input Tree

4.2.3.1 Single Core HVDC Subsea Cable

ABB's XLPE submarine cable systems document [38] was referenced to determine the material inputs required for HVDC subsea cables; these values were then scaled linearly from 330 kV to 525 kV. Table 16, below, shows the percentage mass contribution of the material inputs for the single core HVDC cabling.

Table 16: Single Core HVDC Cable Percentage Mass Contribution

Input	Contribution
Copper	52.04%
Polyethylene	24.35%
Polypropylene	17.30%
Zinc	6.31%

4.2.3.2 Metallic Return Cable

A similar approach was utilized when determining the metallic return cable material inputs; a linear approximation was scaled from ABB's XLPE submarine cable systems document [38]. Table 17, below, shows the percentage mass contribution of the material inputs for the metallic return cabling.

Table 17: Metallic Return Cable Percentage Mass Contribution

Input	Contribution
Steel, Low-Alloyed	56.77%
Polyethylene	21.92%
Polypropylene	15.60%
Zinc	5.71%

4.2.3.3 Fiber Optic Cable

Material inputs for the fiber optic cable were taken from Donovan, 2009, which were directly obtained from Swedish telecom company Ericsson [33]. Table 18, below, shows the percentage mass contribution of the material inputs for the fiber optic cabling.

Table 18: Fiber Optic Cable Percentage Mass Contribution

Input	Contribution
Steel, Low-Alloyed	80.49%
Polypropylene	8.97%
Zinc	5.09%
Bitumen Seal	3.89%
Copper	1.11%
Polyethylene	0.45%
Polypropylene	0.01%

4.3 Installation

The installation of the IJmuiden OWF included the energy and transport associated with all installation activities. Table 19, 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 19: Installation Inputs 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%

4.4 Operation & Maintenance

The IJmuiden OWF is planned to be in continuous operation for a period of 25 years [5]. The O&M strategy for the IJmuiden offshore wind farm was obtained from literature and included the wind turbines' part replacements and associated transportation [39, 40], as well as cable and substation oil replacements [36]. An overview of the O&M input tree can be seen in Figure 14 on the next page.

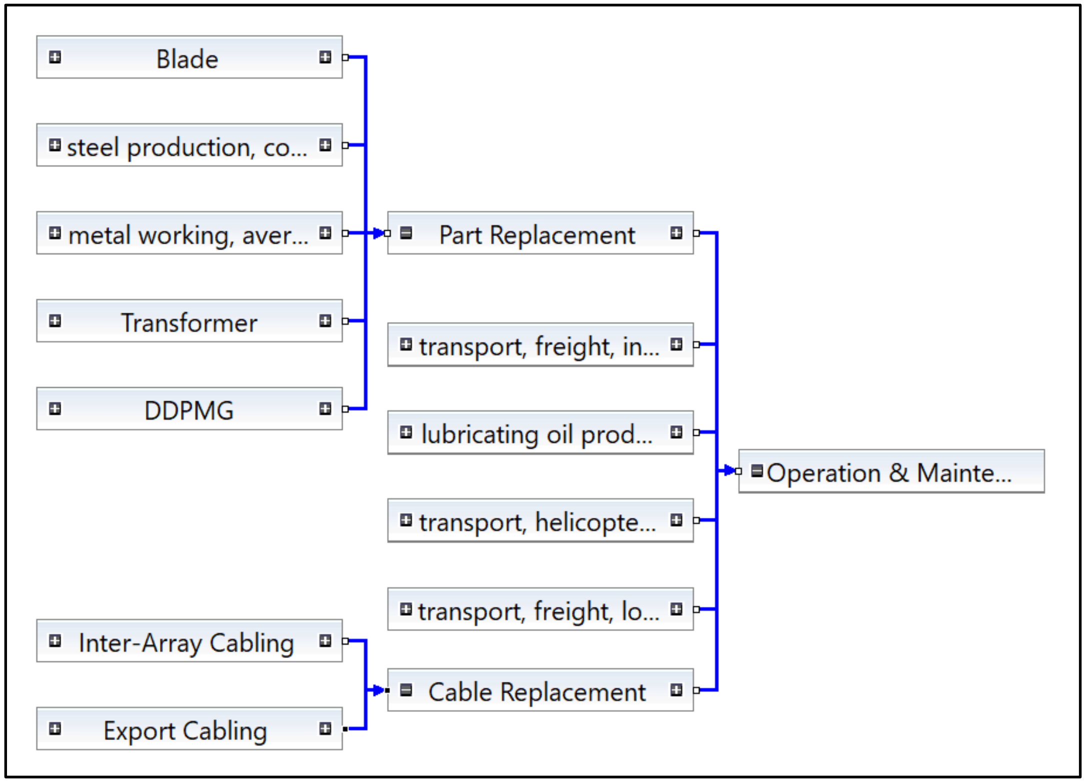

Figure 14: Operation and Maintenance Input Tree

Historically, most of the maintenance related concerns for offshore wind farms has stemmed from the gearbox of offshore turbines [2]. However, the IJmuiden OWF utilizes DD wind turbines which avoids 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 [39, 40]. Regarding cable replacement, both the inter-array and export cabling will require periodic maintenance. Often, repair or replacement work of these cables requires the removal of a section around 1 km. For the IJmuiden OWF it was assumed that a section of 1 km would be required for any cable maintenance [41]. The following table shows the rate of failure for each of the wind farm components over its lifetime. Additional information regarding the O&M transport distances and quantity of substation oil can be found in the supplemental information of this report.

Table 20: Failure Rates for Offshore Wind Farm Components

Component	Rate	Unit	Reference
Blades	0.001%	Failures/turbine/year	[40]
Generator	0.0009%	Failures/turbine/year	[40]
Transformer	0.077%	Failures/turbine/year	[40]
Small Parts	0.362%	Failures/turbine/year	[39]
Inter-Array Cabling	0.003%	Failures/km/year	[41]
Export Cabling	0.003%	Failures/km/year	[41]

4.5 Decommissioning

The decommissioning of the IJmuiden OWF is similar to that of the installation process, it was assumed that wind turbines and electrical infrastructure would be removed at the end of the wind farm's 25-year 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 its EoL [42]. The percentage contribution of the varying decommissioning activities can be found in Table 21, below.

Table 21: Decommissioning Inputs Percentage Contribution

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

4.6 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 [7, 8, 43]. The EoL modeling for the IJmuiden offshore wind farm was divided into hazardous waste incineration, municipal waste incineration, recycling, and landfilling; Table 22, on the next page, shows the EoL methods and ratios for the first scenario.

Table 22: EoL Methods and Ratios for the First Scenario

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

5. Results and Analysis

In this section, the environmental impacts of producing 1 kWh of electricity from the IJmuiden OWF are presented. Three scenarios were modeled, and their associated environmental impacts were quantified. Table 23, below, shows the summarized 18 ReCiPe (H) midpoint impact categories for all three cases. Two impact categories, climate change and metal depletion will be discussed in additional detail. The climate change impact category is of utmost importance when assessing the impact of producing electricity from offshore wind farms and served as a benchmark when comparing to other LCAs. Additionally, the metal depletion impact category was analyzed in further detail, as it is an important parameter when assessing the impact from critical minerals.

Table 23: IJmuiden Offshore Wind Farm Environmental Impacts Summary Table

Domain	Acronym	Scenario 1: 25-Year Lifetime	Scenario 2: 35-Year Lifetime	Scenario 3: Improved CRM Recycling	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

5.1 Scenario 1: 25-Year Operational Lifetime

The first scenario modeled the IJmuiden OWF with a 25-year operational lifetime. Figure 15, on the next page, 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 potential was determined to be 6.51 g CO_2 eq/kWh for the first scenario.

As previously mentioned, in a comprehensive analysis of 126 estimates from 49 studies pertaining to wind power LCAs, a median value of 12 g CO_2 eq/kWh was quantified. The interquartile range (IQR) was found to be 12 g CO_2 eq/kWh and an overall range of 79 g CO_2 eq/kWh, indicating that 50% of the estimations lie within 12 g CO_2 eq/kWh of each other [7]. It is notable, however, that there is significant variation between onshore and offshore LCAs, not only in the number of studies performed but also regarding their associated environmental impacts. Onshore wind LCAs have been performed far more often, 107 estimates, and have a larger total range of values – the IQR for onshore LCAs is 13 g CO_2 eq/kWh, ranging from 7.3 to 20 g CO_2 eq/kWh. Whereas offshore LCAs, 16 estimates, have an IQR of 5 g CO_2 eq/kWh and a range of 9.4 to 14 g CO_2 eq/kWh. However, this range was further adjusted by Mendecka and Lombardi, incorporating the most recent offshore wind LCAs, quantified at 7.8 – 32 g CO_2 eq/kWh. [22].

The global warming potential quantified for the IJmuiden OWF showed a 17% decrease when comparing to the lower bound found by Mendecka and Lombardi and can be explained for several reasons. As mentioned in the literature review, 80 out of 107 LCAs analyzed by Dolan and Heath reported a wind farm lifetime of 20 years [7]. 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.

Figure 15, below, shows the relative contribution of each life cycle process to the ReCiPe (H) midpoint impact categories, with an additional breakdown of the wind turbine into its two primary inputs – the RNA and support structure.

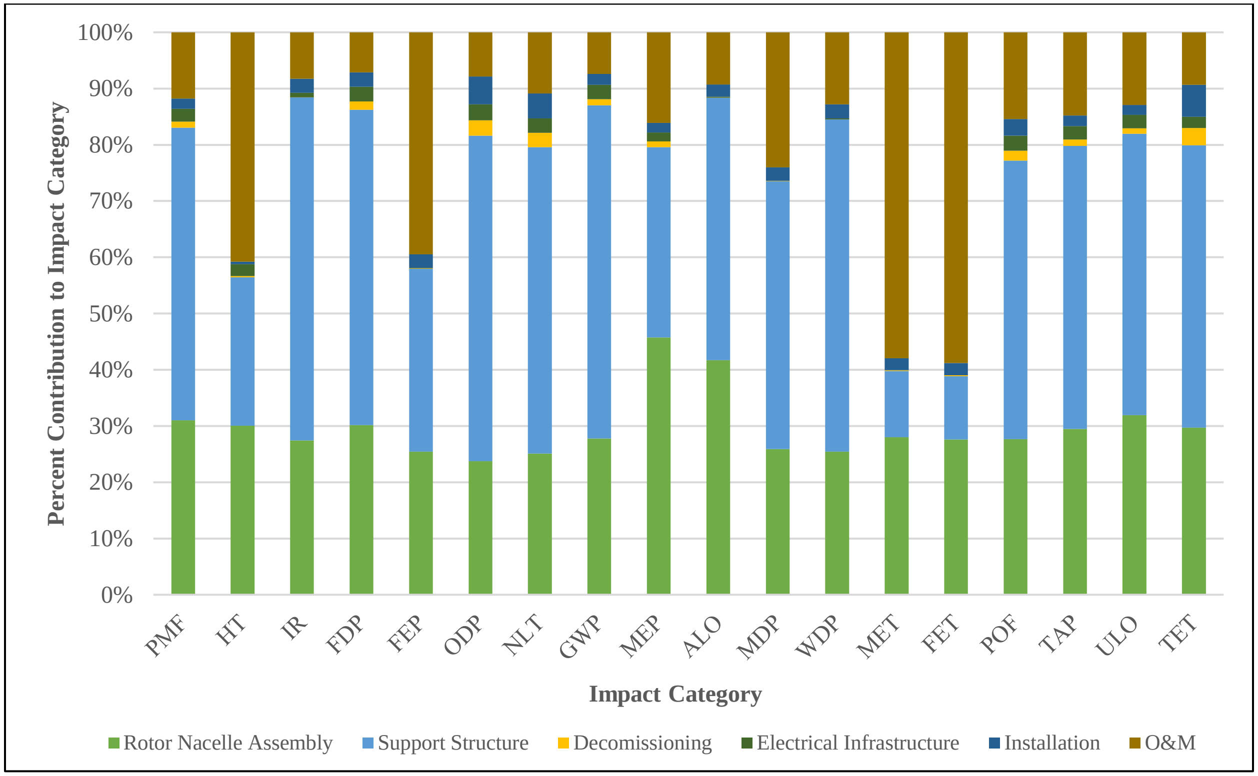

Figure 15: Scenario 1 – Relative Contribution of Each Life Cycle Process to the Impact Categories

5.2 Scenario 2: 35-Year Operational Lifetime

An analysis and discussion of the second scenario can be found in the following subsection of this report. 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 [39, 40, 41]. 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. The following figure 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.

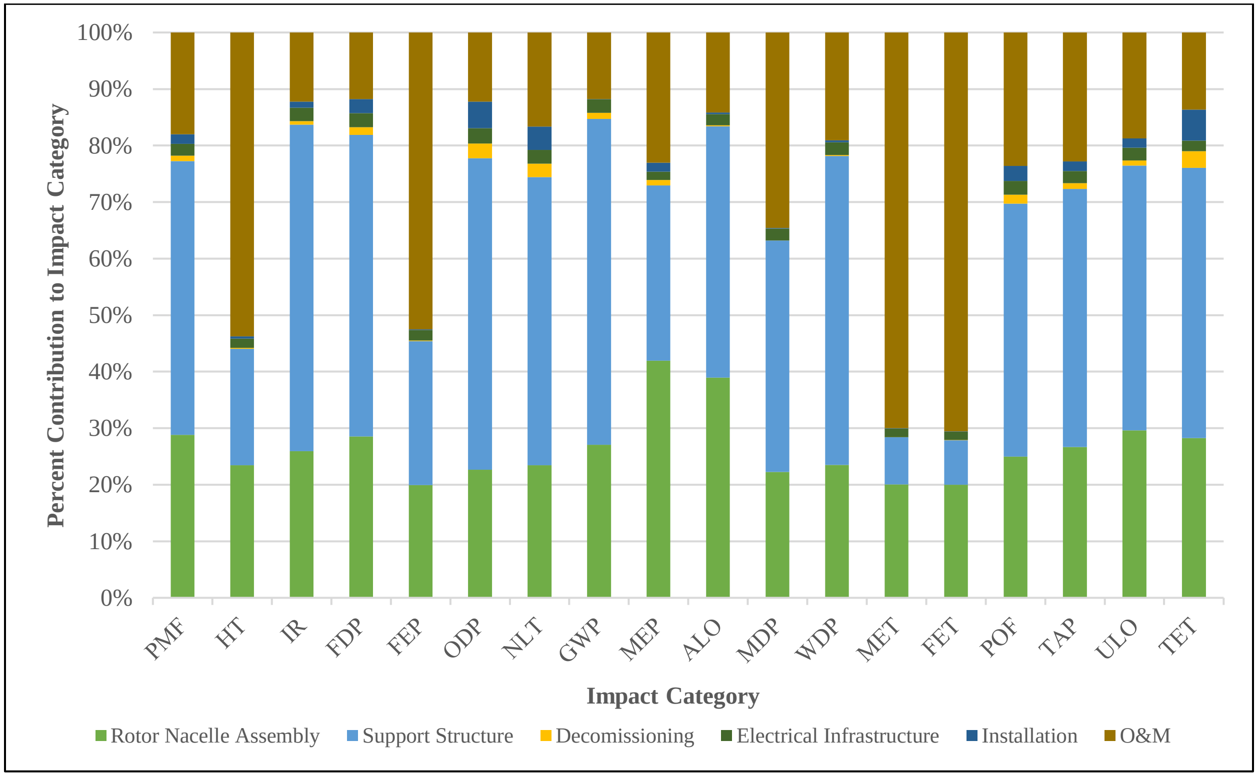

Figure 16: Scenario 2 – Relative Contribution of Each Life Cycle Process to the Impact Categories

5.2 Scenario 3: Improved Critical Raw Material Recycling

The European Union has noted that the improved recycling of wind turbines could help meet 22% of nickel, 10% of neodymium, and 11% of dysprosium requirements for new wind power installations [16]. As outlined in the Critical Raw Materials Act, the EU has indicated that no third country should supply more than 65% of the annual consumption of each critical raw material; the Figure 17, on the next page, shows the global distribution of critical raw materials supply [16]. If achieved, the EU's ability to monitor and mitigate the CRM supply risk would significantly increase – ultimately ensuring that the offshore wind industry can continue its rapid scale up, further enabling circularity and sustainability throughout its supply chain.

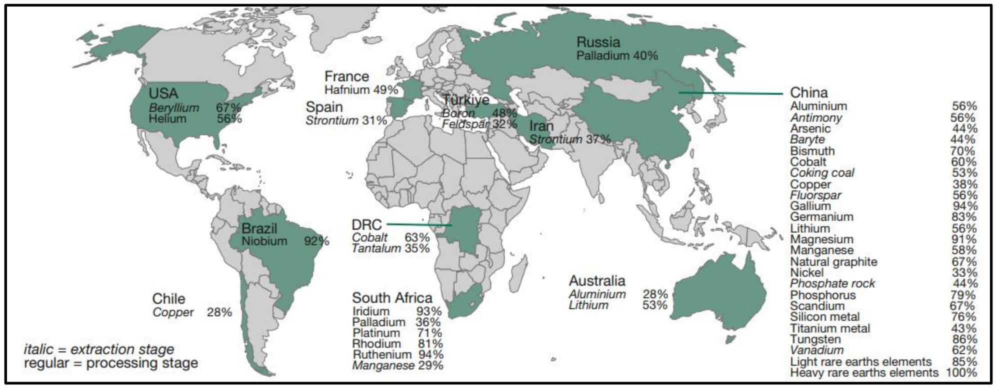

Figure 17: Global Distribution of Critical Raw Materials Supply [16]

In order to aid in this goal, the third 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. The following figure shows the percentage contribution of each impact category for the improved CRM recycling scenario; a more detailed impact category breakdown can be found in the supplemental information of this report.

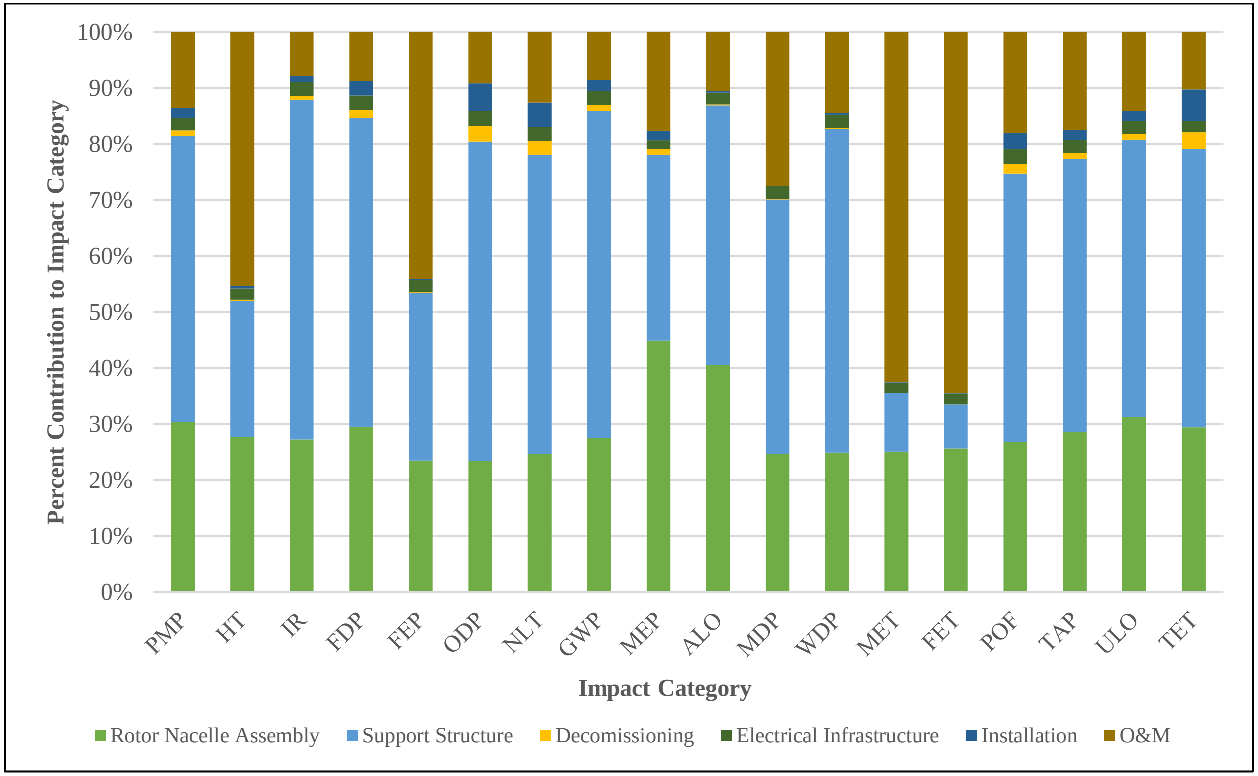

Figure 18: Scenario 3 – Relative Contribution of Each Life Cycle Process to the Impact Categories

5.4 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 19, below, 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 [22]. Additionally, the utilization of larger capacity wind farms and HVDC infrastructure allows for more efficient electricity transmission, which explains the reduced environmental impacts.

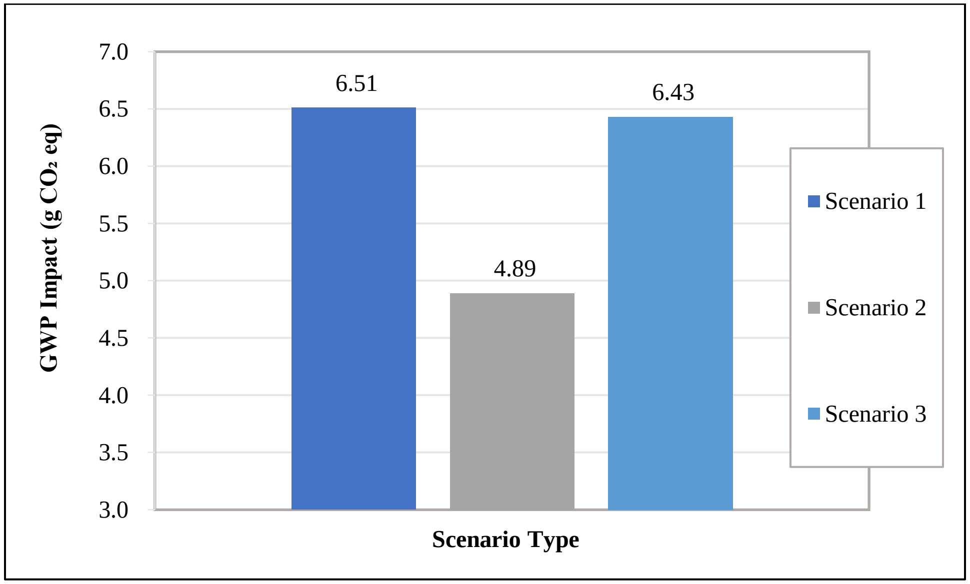

Figure 19: Global Warming Potential for the Three Scenarios

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 Netherlands' RBC and 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. Currently, the recycling rates of the CRMs utilized in the DDPMG of offshore wind turbines is less than 0.3%, the EU aims to improve this rate to 15% by 2030 [16].

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 20, below, 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.

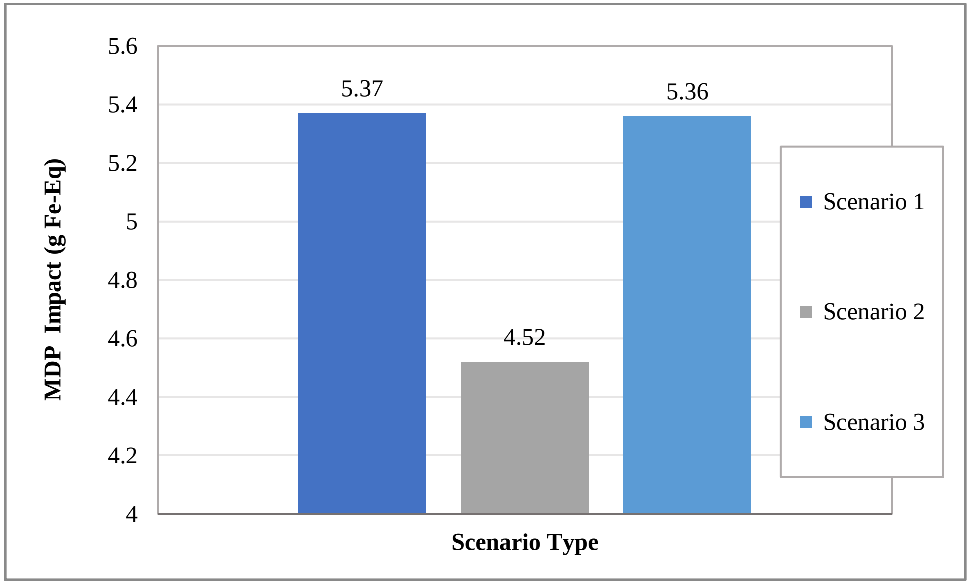

Figure 20: Metal Depletion for the Three Scenarios

5.4.1 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 21, on the following page, shows the global warming potential for the second tier of inputs for the offshore wind turbine.

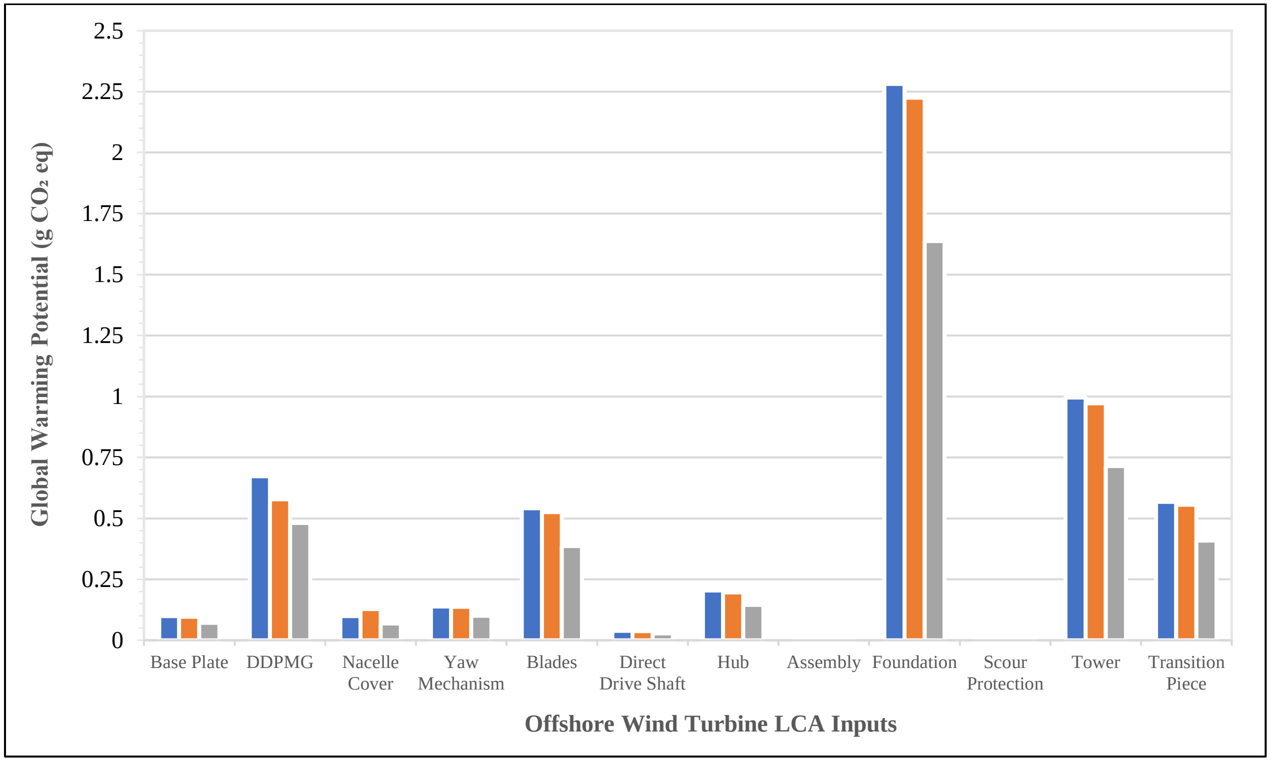

Figure 21: Offshore Wind Turbine Global Warming Potential Environmental Impacts

As can be seen in the figure, 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.

5.4.2 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, 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%.

5.4.3 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.

5.4.4 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%.

5.4.5 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.

6. 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 [5]. Much of the technical data and site information utilized during the LCA modeling was obtained from the Netherlands' development framework for offshore wind energy [5], TNO's offshore wind decommissioning document [18], and the IEA's 15 MW reference turbine document [20]. 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 [22]. 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 60-90% less energy intensive than primary production using metal ores [44], 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.

6.1 Recommendations and Further Work

The following subsection 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 piece-less 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. As identified in section 4.6, 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 [7, 8, 43]. 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 [39, 40, 41]. 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 failures 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 a HVAC offshore substation and scaled accordingly [36]. 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 [15].

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Supplemental Information (SI)

Table 1: IJmuiden Offshore Wind Farm Aggregated Inventory Dataset

	Domain	**Quantity**	**Total**	**Unit**
Inputs	*Offshore Turbine*	*134*	*6.53E+08*	*t*
	Electrical Infrastructure	*1*	*6.05E+04*	*t*
	Installation	*1*	*1*	*items*
	Operation and Maintenance	*1*	*1*	*items*
	Decommissioning	*1*	*1*	*items*
	End-of-Life	*1*	*1*	*items*
Total	*IJmuiden Offshore Wind Farm net annual yield*	*1*	*8.97E+03*	*GWh*
	IJmuiden Offshore Wind Farm net total yield (base case: 25-year lifetime)	*1*	*2.24E+05*	*GWh*
	IJmuiden Offshore Wind Farm net total yield (scenario 1: 35-year lifetime)	*1*	*3.14E+05*	*GWh*

Table 2: Offshore Turbine Aggregated Inventory Dataset

	Domain	**Quantity**	**Total**	**Unit**
Inputs	*Support Structure*	*1*	*8.18E+03*	*t*
	Rotor Nacelle Assembly	*1*	*1.07E+03*	*t*
Total	*Offshore Turbine mass*	*1*	*9.24E+03*	*t*

Table 3: Support Structure Aggregated Inventory Dataset

	Domain	**Quantity**	**Total**	**Unit**
Inputs	*Tower*	*1*	*2.00E+03*	*t*
	Transition Piece	*1*	*5.00E+02*	*t*
	Foundation	*1*	*4.87E+03*	*t*
	Scour Protection	*1*	*8.05E+02*	*t*
Total	*Support Structure mass*	*1*	*8.18E+03*	*t*

Table 4: Tower Aggregated Inventory Dataset

	Domain	**Location**	**Value**	**Unit**
Manufacturing	Steel, low-alloyed	NL	7.90E+05	kg
	Aluminum, primary, ingot	NL	1.45E+04	kg
Processing	Metal working, average for steel product manufacturing	NL	7.90E+05	kg
	Metal working, average for aluminum product manufacturing	NL	1.45E+04	kg
	Heavy fuel oil	NL	6.26E+03	kg
	Tap water	NL	1.26E+04	kg
	Welding, arc, steel	NL	2.02E+01	m
Energy	Heat, district or industrial, natural gas	NL	8.05E+01	kWh
	Electricity, medium voltage, label-certified	NL	1.11E+04	kWh
	Diesel, burning in diesel-electric generator	NL	1.61E+01	kWh
Waste	Hazardous waste, for underground deposit	NL	8.05E+01	kg
	Inert waste	NL	1.11E+04	kg
	Disposal, used mineral oil, 10% water, to hazardous waste incineration	NL	1.61E+01	kg
Total	Tower mass	NL	8.05E+05	kg

Table 5: Transition Piece Aggregated Inventory Dataset

	Domain	**Location**	**Value**	**Unit**
Manufacturing	Cement, unspecified	UK	6.50E+03	kg
	Steel, low-alloyed	UK	7.50E+03	kg
	Aluminum, primary, ingot	UK	4.86E+05	kg
Processing	Metal working, average for steel product manufacturing	UK	4.86E+05	kg
	Welding, arc, steel	UK	1.50E+01	m
Energy	Heat, district or industrial, natural gas	UK	9.65E+03	kWh
	Electricity, medium voltage, label-certified	UK	5.11E+04	kWh
	Diesel, burning in diesel-electric generator	UK	2.50E+03	kWh
Waste	Hazardous waste, for underground deposit	UK	5.00E+01	kg
	Inert waste	UK	6.90E+03	kg
	Disposal, used mineral oil, 10% water, to hazardous waste incineration	UK	1.00E+01	kg
Total	Transition Piece mass	UK	5.00E+05	kg

Table 6: Foundation Aggregated Inventory Dataset

	Domain	**Location**	**Value**	**Unit**
Manufacturing	Cement, unspecified	NL	2.60E+04	kg
	Steel, low-alloyed	NL	3.00E+04	kg
	Aluminum, primary, ingot	NL	1.94E+06	kg
Processing	Metal working, average for steel product manufacturing	NL	1.94E+06	kg
	Welding, arc, steel	NL	7.30E+01	m
Energy	Heat, district or industrial, natural gas	NL	3.86E+04	kWh
	Electricity, medium voltage, label-certified	NL	2.04E+05	kWh
	Diesel, burning in diesel-electric generator	NL	1.00E+04	kWh
Waste	Hazardous waste, for underground deposit	NL	2.00E+02	kg
	Inert waste	NL	2.76E+04	kg
	Disposal, used mineral oil, 10% water, to hazardous waste incineration	NL	4.00E+01	kg
Total	Foundation mass	NL	2.00E+06	kg

Table 7: Scour Protection Aggregated Inventory Dataset

	Domain	**Location**	**Value**	**Unit**
Manufacturing	Gravel, round	DE	4.87E+06	kg
	Textile, non-woven polypropylene	NL	4.20E+02	kg
Total	Scour Protection mass	NL	4.87E+06	kg

Table 8: Rotor Nacelle Assembly Aggregated Inventory Dataset

	Domain	**Quantity**	**Total**	**Unit**
Inputs	*Rotor*	*1*	*4.23E+02*	*t*
	Nacelle	*1*	*6.42E+02*	*t*
	Assembly	*1*	*1.00E+00*	*item*
Total	*Rotor Nacelle Assembly mass*	*1*	*1.07E+03*	*t*

Table 9: Rotor Aggregated Inventory Dataset

	Domain	**Quantity**	**Total**	**Unit**
Inputs	*Hub*	*1*	*2.27E+02*	*t*
	Blades	*3*	*1.96E+02*	*t*
Total	*Rotor mass*	*1*	*4.23E+02*	*t*

Table 10: Hub Aggregated Inventory Dataset

	Domain	**Location**	**Value**	**Unit**
Manufacturing	Cast iron	NL	1.05E+05	kg
	Glass fiber reinforced plastic, polyester resin, hand lay-up	NL	6.36E+03	kg
	Steel, chromium steel 18/8	NL	6.11E+04	kg
	Steel, low-alloyed	NL	5.50E+04	kg
Processing	Metal working, average for metal product manufacturing	NL	1.05E+05	kg
	Metal working, average for chromium steel product manufacturing	NL	6.11E+04	kg
	Metal working, average for steel product manufacturing	NL	5.50E+04	kg
	Silica Sand	NL	9.09E+05	kg
	Tap Water	NL	9.93E+04	kg
Energy	Natural gas, burned in gas motor, for storage	NL	1.14E+05	kWh
	Electricity, medium voltage, label-certified	NL	2.76E+05	kWh
Total	Hub mass	NL	2.27E+05	kg

Table 11: Blade Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Epoxy resin, liquid	NL	1.72E+04	kg
	Glass fiber reinforced plastic, polyester resin, hand lay-up	NL	4.36E+04	kg
	Polypropylene, granulate	NL	1.24E+03	kg
	Sawnwood, paraná pine, dried (u=10%)	BR	5.81E+00	m³
Processing	Tap water	NL	6.71E+04	kg
Energy	Heat, district or industrial, natural gas	NL	1.28E+05	kWh
	Natural gas, burned in gas motor, for storage	NL	2.24E+04	kWh
	Electricity, medium voltage, label-certified	NL	4.48E+04	kWh
Total	Blade mass	NL	6.52E+04	kg

Table 12: Nacelle Aggregated Inventory Dataset

	Domain	Quantity	Total	Unit
Inputs	*Nacelle Cover*	*1*	*3.64E+01*	*t*
	Direct Drive Permanent Magnet Generator	*1*	*4.41E+02*	*t*
	Base Plate	*1*	*7.50E+01*	*t*
	Direct Drive Shaft	*1*	*1.58E+01*	*t*
	YAW Mechanism	*1*	*7.40E+01*	*t*
Total	*Nacelle mass*	*1*	*6.42E+02*	*t*

Table 13: Nacelle Cover Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Epoxy resin, liquid	NL	1.20E+04	kg
	Glass fiber reinforced plastic, polyester resin, hand lay-up	NL	1.80E+04	kg
	Steel, chromium steel 18/8	NL	6.36E+03	kg
Processing	Metal working, average for chromium steel product manufacturing	NL	6.36E+03	kg
Energy	Heat, district or industrial, natural gas	NL	2.78E+04	kWh
	Electricity, medium voltage, label-certified	NL	5.06E+03	kWh
Total	Nacelle Cover mass	NL	3.64E+04	kg

Table 14: Direct-Drive Permanent Magnet Generator Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Aluminum, primary, ingot	NL	3.63E+01	kg
	Boric oxide	NL	1.33E+02	kg
	Cast iron	NL	4.15E+05	kg
	Soft iron, magnet core	NL	8.02E+03	kg
	Dysprosium (Critical Raw Material)	CN	1.21E+02	kg
	Ferroniobium (Critical Raw Material)	BR	9.67E+01	kg
	Neodymium Oxide (Critical Raw Material)	CN	3.69E+03	kg
	Copper, cathode	NL	1.40E+04	kg
Processing	Metal working, average for metal product manufacturing	NL	4.23E+05	kg
	Metal working, average for aluminum product manufacturing	NL	3.63E+01	kg
	Wire drawing, copper	NL	1.40E+04	kg
Energy	Heat, district or industrial, natural gas	NL	6.14E+04	kWh
	Electricity, medium voltage, label-certified	NL	3.37E+05	kWh
Total	Direct-Drive Permanent Magnet Generator mass	NL	4.41E+05	kg

Table 15: Base Plate Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Spheroidal graphite cast iron	NL	7.50E+04	kg
Processing	Metal working, average for metal product manufacturing	NL	7.50E+04	kg
Energy	Heat, district or industrial, natural gas	NL	5.74E+04	kWh
	Electricity, medium voltage, label-certified	NL	1.04E+04	kWh
Total	Base Plate mass	NL	7.50E+04	kg

Table 16: Direct-Drive Shaft Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Steel, chromium steel 18/8	NL	1.58E+04	kg
Processing	Metal working, average for metal product manufacturing	NL	1.58E+04	kg
Energy	Heat, district or industrial, natural gas	NL	1.20E+04	kWh
	Electricity, medium voltage, label-certified	NL	2.19E+03	kWh
Total	Direct-Drive Shaft mass	NL	1.58E+04	kg

Table 17: Yaw Mechanism Aggregated Inventory Dataset

	Domain	**Location**	**Value**	**Unit**
Manufacturing	Steel, chromium steel 18/8	NL	1.06E+03	kg
	Cast iron	NL	3.64E+04	kg
	Copper, cathode	NL	3.64E+04	kg
Processing	Metal working, average for chromium steel manufacturing	NL	1.06E+03	kg
	Metal working, average for metal product manufacturing	NL	3.64E+04	kg
	Wire drawing, copper	NL	3.64E+04	kg
Energy	Heat, district or industrial, natural gas	NL	5.66E+04	kWh
	Electricity, medium voltage, label-certified	NL	1.03E+04	kWh
Total	Direct-Drive Shaft mass	NL	7.40E+04	kg

Table 18: Assembly Aggregated Inventory Dataset

	Domain	**Location**	**Value**	**Unit**
Manufacturing	Tap Water	NL	1.22E+05	kg
Energy	Heat, district or industrial, natural gas	NL	4.12E+03	kWh
	Natural gas, burned in gas motor, for storage	NL	4.20E+04	kWh
	Electricity, medium voltage, label-certified	NL	5.60E+04	kWh

Table 19: Electrical Infrastructure Aggregated Inventory Dataset

	Domain	**Quantity**	**Total**	**Unit**
Inputs	*Offshore Converterstation*	*1*	*3.22E+04*	*t*
	Onshore Substation	*1*	*1.53E+04*	*t*
	66 kV Inter-array Cabling	*1*	*2.37E+02*	*km*
	525 kV Export Cabling	*1*	*1.46E+02*	*km*
Total	*Electrical Infrastructure mass*	*1*	*7.34E+04*	*t*

Table 20: Offshore Converterstation Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Sand	NL	3.07E+05	kg
	Epoxy Resin, liquid	NL	3.85E+04	kg
	Steel, low-alloyed	NL	2.20E+07	kg
	Aluminum, primary, ingot	NL	1.68E+05	kg
	Nickel, class 1	NL	4.61E+01	kg
	Alkyd paint production, white, solvent-based	NL	8.15E+02	kg
	Cast iron	NL	1.66E+03	kg
	Steel, chromium steel 18/8	NL	6.69E+03	kg
	Copper, cathode	NL	2.25E+05	kg
	Glass fiber reinforced plastic, polyamide, injection molded	NL	9.50E+03	kg
	Kraft paper	NL	1.54E+02	kg
	Lubricating oil	NL	4.11E+05	kg
	Polycarbonate	NL	7.69E+01	kg
	Polyester resin	NL	1.23E+03	kg
	Polyethylene, high density, granulate	NL	3.38E+02	kg
	Structural timber	NL	4.14E+01	m^3
	Silver	NL	1.54E+01	kg
	Sulfate pulp, unbleached	NL	4.53E+04	kg
	Sulfur hexafluoride, liquid	NL	8.21E+03	kg
	Synthetic rubber	NL	9.99E+02	kg
	Gravel, round	NL	8.89E+06	kg
Processing	Metal working, average for steel product manufacturing	NL	2.20E+07	kg
	Metal working, average for aluminum product manufacturing	NL	1.68E+05	kg
	Metal working, average for metal product manufacturing	NL	1.66E+03	kg
	Metal working, average for chromium steel product manufacturing	NL	6.69E+03	kg
	Welding, arc, steel	NL	1.71E+04	m
	Wire drawing, copper	NL	2.25E+05	kg
Energy	Natural gas, burned in gas motor	NL	4.29E+06	kWh
	Electricity, medium voltage, label-certified	NL	4.23E+06	kWh
	Diesel, burning in diesel-electric generator	NL	1.64E+06	kWh
	Heavy fuel oil, burned in refinery furnace	NL	6.14E+05	kWh
Total	Offshore Converterstation mass	NL	3.21E+07	kg

Table 21: Onshore Substation Aggregated Inventory Dataset

	Domain	**Location**	**Value**	**Unit**
Manufacturing	Sand	NL	1.46E+05	kg
	Epoxy Resin, liquid	NL	1.83E+04	kg
	Steel, low-alloyed	NL	1.04E+07	kg
	Aluminum, primary, ingot	NL	8.01E+04	kg
	Nickel, class 1	NL	2.19E+01	kg
	Alkyd paint production, white, solvent-based	NL	3.87E+02	kg
	Cast iron	NL	7.90E+02	kg
	Steel, chromium steel 18/8	NL	3.18E+03	kg
	Copper, cathode	NL	1.07E+05	kg
	Glass fiber reinforced plastic, polyamide, injection molded	NL	4.52E+03	kg
	Kraft paper	NL	7.31E+01	kg
	Lubricating oil	NL	1.96E+05	kg
	Polycarbonate	NL	3.66E+01	kg
	Polyester resin	NL	5.85E+02	kg
	Polyethylene, high density, granulate	NL	1.61E+02	kg
	Structural timber	NL	1.97E+01	m^3
	Silver	NL	7.31E+00	kg
	Sulfate pulp, unbleached	NL	2.16E+04	kg
	Sulfur hexafluoride, liquid	NL	3.90E+03	kg
	Synthetic rubber	NL	4.75E+02	kg
	Gravel, round	NL	4.23E+06	kg
Processing	Metal working, average for steel product manufacturing	NL	1.04E+07	kg
	Metal working, average for aluminum product manufacturing	NL	8.01E+04	kg
	Metal working, average for metal product manufacturing	NL	7.90E+02	kg
	Metal working, average for chromium steel product manufacturing	NL	3.18E+03	kg
	Welding, arc, steel	NL	8.15E+03	m
	Wire drawing, copper	NL	1.07E+05	kg
Energy	Natural gas, burned in gas motor	NL	2.04E+06	kWh
	Electricity, medium voltage, label-certified	NL	2.01E+06	kWh
	Diesel, burning in diesel-electric generator	NL	7.82E+05	kWh
	Heavy fuel oil, burned in refinery furnace	NL	2.92E+05	kWh
Total	Onshore Substation mass	NL	1.53E+07	kg

Table 22: 66 kV Inter-array Cabling Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Copper, cathode	NL	1.20E+01	kg
	Polyethylene, high density, granulate	NL	4.00E+00	kg
	Polypropylene, granulate	NL	2.00E+00	kg
	Lead	NL	1.60E+01	kg
	Steel, low-alloyed	NL	2.40E+01	kg
Processing	Wire drawing, steel	NL	2.40E+01	kg
	Wire drawing, copper	NL	1.20E+01	kg
Energy	Electricity, medium voltage, label-certified	NL	7.37E+01	kWh
	Natural gas, burned in gas motor	NL	7.77E+01	kWh
Total	Inter-array Cabling mass (per meter)	NL	5.80E+01	kg

Table 23: 525 kV Export Cabling Aggregated Inventory Dataset

	Domain	Quantity	Total	Unit
Inputs	*Single Core HVDC Subsea Cable*	*2*	*2.00E+02*	*kg*
	Metallic Return Cable	*1*	*2.77E+01*	*kg*
	Fiber Optic Cable	*1*	*5.40E+00*	*kg*
Total	*525 kV Export Cabling mass (per meter)*	*1*	*2.33E+02*	*kg*

Table 24: Single Core HVDC Subsea Cable Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Copper, cathode	NL	5.19E+01	kg
	Zinc	NL	6.30E+00	kg
	Polyethylene, high density, granulate	NL	2.43E+01	kg
	Polypropylene, granulate	NL	1.73E+01	kg
Processing	Wire drawing, copper	NL	5.19E+01	kg
	Zinc coat, coils	NL	9.28E+00	m²
Energy	Electricity, medium voltage, label-certified	NL	4.00E+02	kWh
	Heat, district or industrial, natural gas	NL	7.59E+02	kWh
Total	Single Core HVDC Subsea Cable (per meter)	NL	*9.98E+01*	kg

Table 25: Metallic Return Cable Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Steel, low-alloyed	NL	1.57E+01	kg
	Polyethylene, high density, granulate	NL	6.07E+00	kg
	Polypropylene, granulate	NL	4.32E+00	kg
	Zinc	NL	1.58E+00	kg
Processing	Wire drawing, steel	NL	1.57E+01	kg
	Zinc coat, coils	NL	2.33E+00	m²
Energy	Electricity, medium voltage, label-certified	NL	1.11E+02	kWh
	Natural gas, burned in gas motor	NL	2.11E+02	kWh
Total	Inter-array Cabling mass (per meter)	NL	2.77E+01	kg

Table 26: Fiber Optic Cable Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Steel, low-alloyed	NL	4.35E+00	kg
	Copper, cathode	NL	6.00E-02	kg
	Zinc	NL	2.75E-01	kg
	Polyethylene, high density, granulate	NL	2.41E-02	kg
	Polypropylene, granulate	NL	4.85E-01	kg
	Glass fiber reinforced plastic, polyamide, injection molded	NL	2.90E-04	kg
	Bitumen Seal	NL	2.10E-01	kg
Processing	Wire drawing, copper	NL	6.00E-02	kg
	Zinc coat, coils	NL	4.05E-01	m²
	Wire drawing, steel	NL	4.35E+00	kg
Energy	Electricity, medium voltage, label-certified	NL	2.17E+01	kWh
	Natural gas, burned in gas motor	NL	4.11E+01	kWh
Total	Inter-array Cabling mass (per meter)	NL	5.40E+00	kg

Table 27: Installation Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Land Transport	Transport of Rotor, lorry >32 ton	NL	4.25E+07	t*km
	Transport of Nacelle, lorry >32 ton	NL	6.46E+07	t*km
	Transport of Scour Protection, lorry >32 ton	NL	1.68E+08	t*km
	Transport of Inter-array Cabling, lorry >32 ton	NL	1.84E+07	t*km
	Transport of Export Cabling, lorry >32 ton	NL	5.67E+07	t*km
	Transport of Offshore Converterstation, lorry >32 ton	NL	4.82E+06	t*km
	Transport of Onshore Substation, lorry >32 ton	NL	2.29E+06	t*km
Sea Transport	Transport of Rotor, barge	NL	8.50E+06	t*km
	Transport of Nacelle, barge	NL	1.29E+07	t*km
	Transport of Tower, barge	NL	1.62E+07	t*km
	Transport of Transition Piece, barge	NL	8.38E+07	t*km
	Transport of Foundation, barge	NL	4.02E+07	t*km
	Transport of Scour Protection, barge	NL	9.79E+07	t*km
	Transport of Inter-array Cabling, barge	NL	2.06E+06	t*km
	Transport of Export Cabling, barge	NL	5.09E+06	t*km
	Transport of Offshore Converterstation, barge	NL	2.41E+06	t*km
Total	Land Transport	NL	3.58E+08	t*km
	Sea Transport	NL	2.69E+08	t*km

Table 28: Operation and Maintenance Aggregated Inventory Dataset

	Domain	Quantity	Total	Unit
Inputs	*Part Replacement, Rotor Blades*	*134*	*2.19E+02*	*t*
	Part Replacement, Direct-Drive Permanent Magnet Generator	*134*	*1.33E+04*	*t*
	Part Replacement, Transformer	*134*	*1.88E+04*	*t*
	Part Replacement, Small Parts	*134*	*1.82E+03*	*t*
	Substation, Lubricating Oil	*1*	*1.75E+03*	*t*
	Cable Replacement, Inter-array	*1*	*1.77E+01*	*km*
	Cable Replacement, Export	*1*	*1.10E+01*	*km*
Land Transport	Transport of Blades, lorry >32 ton	1	3.28E+04	t*km
	Transport of Direct-Drive Permanent Magnet Generator, lorry >32 ton	1	2.00E+06	t*km
	Transport of Transformer, lorry >32 ton	1	2.81E+03	t*km
	Transport of Small Parts, lorry >32 ton	1	2.73E+05	t*km
	Transport of Lubricating Oil, lorry >32 ton	1	5.04E+04	t*km
	Transport of Inter-array Cabling, lorry >32 ton	1	1.54E+05	t*km
	Transport of Export Cabling, lorry >32 ton	1	3.82E+05	t*km
Sea Transport	Transport of Blades, barge	1	1.64E+05	t*km
	Transport of Direct-Drive Permanent Magnet Generator, barge	1	9.98E+06	t*km
	Transport of Transformer, barge	1	1.41E+04	t*km
	Transport of Small Parts, barge	1	1.36E+06	t*km
	Transport of Lubricating Oil, barge	1	3.13E+05	t*km
	Transport of Inter-array Cabling, barge	1	1.38E+06	t*km
	Transport of Export Cabling, barge	1	4.25E+06	t*km
Air Transport	Transport, helicopter	1	2.50E+04	flight-hours
Total	*Land Transport*	*1*	*1.75E+07*	*t*km*
	Sea Transport	*1*	*2.89E+06*	*t*km*
	Air Transport	*1*	*2.50E+04*	*flight-hours*
	O&M mass	*1*	*3.94E+04*	*t*

Table 29: Transformer Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Cast iron	NL	8.40E+04	kg
	Copper, cathode	NL	4.20E+04	kg
	Aluminum, primary, ingot	NL	1.40E+04	kg
Total	Scour Protection mass	NL	1.40E+05	kg

Table 30: Small Parts Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Manufacturing	Steel, low-alloyed	NL	1.36E+04	kg
Processing	Metal working, average for steel product manufacturing	NL	1.36E+04	kg
Total	Small Parts mass	NL	1.36E+04	kg

Table 31: Decommissioning Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Land Transport	Transport of Rotor, lorry >32 ton	NL	4.25E+07	t*km
	Transport of Nacelle, lorry >32 ton	NL	6.46E+07	t*km
	Transport of Inter-array Cabling, lorry >32 ton	NL	1.84E+07	t*km
	Transport of Export Cabling, lorry >32 ton	NL	5.67E+07	t*km
	Transport of Offshore Converterstation, lorry >32 ton	NL	4.82E+06	t*km
	Transport of Onshore Substation, lorry >32 ton	NL	2.29E+06	t*km
Sea Transport	Transport of Rotor, barge	NL	8.50E+06	t*km
	Transport of Nacelle, barge	NL	1.29E+07	t*km
	Transport of Tower, barge	NL	1.62E+07	t*km
	Transport of Transition Piece, barge	NL	8.38E+07	t*km
	Transport of Foundation, barge	NL	4.02E+07	t*km
	Transport of Inter-array Cabling, barge	NL	2.06E+06	t*km
	Transport of Export Cabling, barge	NL	5.09E+06	t*km
	Transport of Offshore Converterstation, barge	NL	2.41E+06	t*km
Total	Land Transport	NL	1.89E+08	t*km
	Sea Transport	NL	1.71E+08	t*km

Table 32: End-of-Life Aggregated Inventory Dataset

	Domain	Location	Value	Unit
Inputs	Disposal, silver, to recycling	NL	1.11E+01	kg
	Disposal, nickel, to recycling	NL	2.31E+01	kg
	Disposal, ferroniobium, to recycling	NL	4.76E+01	kg
	Disposal, dysprosium, to recycling	NL	5.95E+01	kg
	Disposal, neodymium oxide, to recycling	NL	6.05E+03	kg
	Disposal, zinc, to recycling	NL	2.16E+06	kg
	Disposal, aluminum, to recycling	NL	3.55E+06	kg
	Disposal, lead, to recycling	NL	3.86E+06	kg
	Disposal, polypropylene, to recycling	NL	5.25E+06	kg
	Disposal, polyethylene, to recycling	NL	7.18E+06	kg
	Disposal, wood, untreated, to recycling	NL	1.20E+07	kg
	Disposal, copper, to recycling	NL	2.35E+07	kg
	Disposal, cast iron, to recycling	NL	9.87E+07	kg
	Disposal, steel, to recycling	NL	4.30E+08	kg
	Disposal, inert waste, to inert material landfill	NL	5.25E+06	kg
	Disposal, municipal waste, to municipal waste incineration	NL	9.39E+07	kg
	Disposal, hazardous waste, to hazardous waste incineration	NL	1.03E+07	kg
Total	EoL mass	NL	7.00E+08	kg

Table 33: IJmuiden Offshore Wind Farm Environmental Impacts Summary Table

Domain	Acronym	Scenario 1: 25-Year Lifetime	Scenario 2: 35-Year Lifetime	Scenario 3: Improved CRM Recycling	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

Table 34: Scenario 1: 25-year Lifetime Percentage Contribution to Impact Categories

Domain	GWP	TAP	ODP	ALO	ULO	NLT	FDP	MDP	WDP	FET	MET	TET	HT	FEP	MEP	IR	PMF	POF
Offshore Turbine	**87%**	**80%**	**82%**	**88%**	**82%**	**80%**	**86%**	**74%**	**85%**	**39%**	**40%**	**80%**	**56%**	**58%**	**80%**	**88%**	**83%**	**77%**
Support Structure	59%	50%	58%	47%	50%	54%	56%	48%	59%	11%	12%	50%	26%	32%	34%	61%	52%	50%
Foundation	35%	29%	34%	28%	30%	32%	33%	29%	35%	7%	7%	30%	16%	19%	20%	36%	31%	29%
Tower	15%	14%	15%	12%	13%	14%	15%	12%	15%	2%	3%	13%	6%	8%	9%	16%	14%	13%
Transition Piece	9%	7%	9%	7%	7%	8%	8%	7%	9%	1%	2%	7%	4%	5%	5%	9%	7%	7%
Scour Protection	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	1%
Rotor Nacelle Assembly	28%	29%	24%	42%	32%	25%	30%	26%	25%	27%	28%	30%	30%	25%	46%	27%	31%	28%
Nacelle	16%	19%	17%	16%	24%	21%	16%	21%	21%	23%	27%	25%	27%	23%	39%	23%	21%	19%
DDPMG	10%	13%	12%	12%	19%	17%	10%	14%	16%	23%	23%	20%	22%	19%	35%	18%	13%	13%
Yaw Mechanism	2%	3%	2%	1%	2%	2%	2%	4%	2%	1%	2%	2%	2%	2%	2%	2%	4%	2%
Base Plate	2%	2%	2%	1%	1%	2%	2%	1%	2%	0%	1%	2%	2%	1%	1%	2%	2%	2%
Nacelle Cover	2%	1%	1%	0%	1%	0%	1%	1%	1%	0%	1%	0%	1%	0%	1%	1%	1%	1%
Direct-Drive Shaft	1%	1%	0%	2%	0%	0%	1%	1%	0%	0%	0%	1%	0%	0%	0%	0%	1%	1%
Rotor	11%	10%	7%	26%	7%	4%	13%	5%	5%	1%	1%	4%	3%	3%	7%	5%	10%	9%
Blades	8%	7%	4%	23%	5%	2%	11%	5%	2%	0%	0%	1%	1%	2%	5%	3%	5%	6%
Hub	3%	3%	2%	3%	3%	2%	2%	0%	3%	1%	1%	3%	2%	1%	2%	2%	5%	3%
Assembly	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Operation & Maintenance	**7%**	**15%**	**8%**	**9%**	**13%**	**11%**	**7%**	**24%**	**13%**	**58%**	**58%**	**9%**	**41%**	**39%**	**16%**	**8%**	**12%**	**15%**
Part Replacement	5%	0%	6%	8%	10%	8%	4%	20%	11%	48%	48%	8%	34%	33%	14%	7%	10%	13%
Cable Replacement	1%	0%	0%	1%	1%	1%	1%	4%	2%	10%	10%	1%	7%	6%	2%	1%	2%	2%
S.S. Oil Replacement	1%	0%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Helicopter Transport	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Freight Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Barge Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Installation	**2%**	**2%**	**5%**	**2%**	**2%**	**4%**	**3%**	**2%**	**2%**	**2%**	**2%**	**6%**	**0%**	**2%**	**2%**	**3%**	**2%**	**3%**
Freight Transport	1%	1%	4%	1%	1%	2%	2%	1%	1%	1%	1%	6%	0%	1%	1%	2%	1%	2%
Barge Transport	1%	1%	1%	1%	0%	2%	1%	1%	1%	1%	1%	0%	0%	1%	1%	1%	1%	1%
Decommissioning	**1%**	**1%**	**3%**	**0%**	**1%**	**3%**	**1%**	**0%**	**0%**	**0%**	**0%**	**3%**	**0%**	**0%**	**1%**	**0%**	**1%**	**2%**
Freight Transport	1%	1%	2%	0%	1%	1%	1%	0%	0%	0%	0%	3%	0%	0%	1%	0%	1%	1%
Barge Transport	0%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
Electrical Infrastructure	**3%**	**2%**	**3%**	**0%**	**2%**	**3%**	**3%**	**0%**	**0%**	**0%**	**0%**	**2%**	**2%**	**0%**	**2%**	**1%**	**2%**	**3%**
Offshore Converterstation	1%	1%	2%	0%	1%	2%	2%	0%	0%	0%	0%	1%	1%	0%	1%	0%	1%	2%
Onshore Substation	1%	1%	1%	0%	1%	1%	1%	0%	0%	0%	0%	1%	1%	0%	1%	1%	1%	1%
Export Cabling	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Inter-array Cabling	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Table 35: Scenario 2: 35-year Lifetime Percentage Contribution to Impact Categories

Domain	GWP	TAP	ODP	ALO	ULO	NLT	FDP	MDP	WDP	FET	MET	TET	HT	FEP	MEP	IR	PMF	POF
Offshore Turbine	**83%**	**72%**	**78%**	**83%**	**76%**	**74%**	**82%**	**63%**	**78%**	**28%**	**28%**	**76%**	**44%**	**45%**	**73%**	**84%**	**77%**	**70%**
Support Structure	57%	46%	55%	44%	47%	51%	53%	41%	55%	8%	8%	48%	21%	25%	31%	58%	48%	45%
Foundation	33%	27%	32%	27%	28%	30%	32%	25%	33%	5%	5%	29%	12%	15%	18%	34%	28%	26%
Tower	15%	12%	14%	11%	12%	13%	14%	10%	14%	2%	2%	12%	5%	6%	8%	15%	13%	12%
Transition Piece	8%	7%	8%	7%	7%	7%	8%	6%	8%	1%	1%	7%	3%	4%	5%	9%	7%	7%
Scour Protection	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Rotor Nacelle Assembly	27%	27%	23%	39%	30%	23%	29%	22%	24%	20%	20%	28%	23%	20%	42%	26%	29%	25%
Nacelle	16%	18%	16%	15%	23%	20%	16%	18%	19%	19%	19%	24%	21%	18%	36%	21%	19%	17%
DDPMG	10%	12%	11%	10%	18%	15%	9%	12%	15%	17%	17%	19%	17%	15%	32%	17%	12%	12%
Yaw Mechanism	2%	2%	2%	2%	2%	2%	2%	3%	2%	2%	2%	2%	2%	2%	1%	2%	4%	2%
Base Plate	1%	1%	2%	1%	2%	1%	2%	1%	2%	1%	1%	2%	1%	1%	1%	2%	2%	1%
Nacelle Cover	1%	1%	1%	1%	1%	0%	1%	1%	0%	0%	0%	1%	0%	0%	1%	1%	1%	1%
Direct-Drive Shaft	1%	1%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%
Rotor	11%	9%	6%	24%	7%	4%	13%	4%	4%	1%	1%	4%	2%	2%	6%	5%	10%	8%
Blades	8%	6%	4%	21%	4%	2%	10%	4%	3%	0%	0%	1%	1%	1%	5%	3%	5%	5%
Hub	3%	3%	2%	3%	3%	2%	3%	0%	1%	0%	1%	3%	2%	1%	2%	2%	5%	3%
Assembly	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Operation & Maintenance	**12%**	**23%**	**12%**	**14%**	**19%**	**17%**	**12%**	**35%**	**19%**	**71%**	**70%**	**14%**	**54%**	**53%**	**23%**	**12%**	**18%**	**24%**
Part Replacement	10%	19%	10%	12%	16%	14%	9%	29%	17%	58%	58%	12%	45%	43%	21%	11%	15%	19%
Cable Replacement	2%	4%	1%	2%	2%	2%	2%	6%	2%	12%	12%	1%	9%	9%	2%	1%	2%	3%
S.S. Oil Replacement	0%	0%	1%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
Helicopter Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Freight Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Barge Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Installation	**2%**	**2%**	**5%**	**0%**	**2%**	**4%**	**2%**	**0%**	**0%**	**0%**	**0%**	**5%**	**0%**	**0%**	**2%**	**1%**	**2%**	**3%**
Freight Transport	1%	1%	4%	0%	1%	2%	2%	0%	0%	0%	0%	5%	0%	0%	1%	1%	1%	2%
Barge Transport	1%	1%	1%	0%	0%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
Decommissioning	**1%**	**1%**	**3%**	**0%**	**1%**	**2%**	**1%**	**0%**	**0%**	**0%**	**0%**	**3%**	**0%**	**0%**	**1%**	**1%**	**1%**	**2%**
Freight Transport	1%	1%	2%	0%	1%	1%	1%	0%	0%	0%	0%	3%	0%	0%	1%	0%	1%	1%
Barge Transport	0%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
Electrical Infrastructure	**2%**	**2%**	**3%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**1%**	**2%**	**2%**	**2%**
Offshore Converterstation	2%	1%	2%	1%	2%	2%	2%	1%	2%	1%	1%	1%	1%	1%	1%	2%	1%	2%
Onshore Substation	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	1%	1%	1%	0%	1%	1%	1%
Export Cabling	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Inter-array Cabling	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Table 36: Scenario 3: Improved Critical Raw Material Recycling Percentage Contribution to Impact Categories

Domain	GWP	TAP	ODP	ALO	ULO	NLT	FDP	MDP	WDP	FET	MET	TET	HT	FEP	MEP	IR	PMF	POF
Offshore Turbine	**86%**	**77%**	**80%**	**82%**	**81%**	**78%**	**85%**	**70%**	**83%**	**35%**	**36%**	**79%**	**52%**	**53%**	**78%**	**88%**	**81%**	**75%**
Support Structure	58%	49%	57%	46%	49%	53%	55%	45%	58%	8%	10%	50%	24%	30%	33%	61%	51%	48%
Foundation	35%	28%	34%	28%	29%	31%	33%	27%	35%	5%	6%	30%	14%	18%	20%	36%	30%	28%
Tower	15%	13%	15%	12%	13%	14%	14%	11%	15%	2%	3%	13%	6%	8%	9%	16%	13%	12%
Transition Piece	9%	7%	8%	7%	7%	8%	8%	7%	9%	1%	2%	7%	4%	4%	5%	9%	8%	7%
Scour Protection	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Rotor Nacelle Assembly	27%	29%	23%	41%	31%	25%	30%	25%	25%	25%	25%	29%	28%	23%	45%	27%	30%	27%
Nacelle	16%	19%	17%	15%	24%	21%	16%	20%	20%	24%	24%	25%	25%	21%	38%	22%	20%	18%
DDPMG	9%	13%	11%	10%	18%	16%	10%	13%	15%	21%	21%	19%	20%	17%	34%	18%	13%	13%
Yaw Mechanism	2%	3%	2%	2%	2%	2%	2%	4%	2%	2%	2%	2%	2%	2%	1%	2%	4%	2%
Base Plate	2%	2%	2%	1%	2%	2%	2%	1%	2%	1%	1%	2%	2%	1%	1%	2%	2%	2%
Nacelle Cover	2%	1%	1%	1%	1%	0%	1%	1%	0%	0%	0%	1%	0%	0%	1%	1%	1%	1%
Direct-Drive Shaft	1%	1%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
Rotor	11%	10%	7%	25%	7%	4%	13%	5%	5%	1%	1%	4%	3%	2%	7%	5%	10%	9%
Blades	8%	7%	4%	22%	5%	2%	10%	0%	1%	0%	0%	1%	1%	1%	5%	3%	5%	6%
Hub	3%	3%	2%	3%	3%	2%	3%	5%	3%	1%	1%	3%	2%	1%	2%	2%	5%	3%
Assembly	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Operation & Maintenance	**9%**	**17%**	**9%**	**11%**	**14%**	**13%**	**9%**	**27%**	**14%**	**63%**	**63%**	**10%**	**45%**	**44%**	**18%**	**8%**	**14%**	**18%**
Part Replacement	7%	14%	7%	9%	12%	10%	7%	23%	13%	52%	51%	9%	38%	36%	16%	7%	12%	15%
Cable Replacement	1%	3%	1%	1%	2%	2%	1%	5%	2%	11%	11%	1%	8%	8%	2%	1%	2%	3%
S.S. Oil Replacement	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
Helicopter Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Freight Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Barge Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Installation	**2%**	**2%**	**5%**	**0%**	**2%**	**4%**	**3%**	**0%**	**0%**	**0%**	**0%**	**6%**	**0%**	**0%**	**2%**	**1%**	**2%**	**3%**
Freight Transport	1%	1%	4%	0%	1%	2%	2%	0%	0%	0%	0%	5%	0%	0%	1%	1%	1%	2%
Barge Transport	1%	1%	1%	0%	0%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
Decommissioning	**1%**	**1%**	**3%**	**0%**	**1%**	**3%**	**1%**	**0%**	**0%**	**0%**	**0%**	**3%**	**0%**	**0%**	**1%**	**1%**	**1%**	**2%**
Freight Transport	1%	1%	2%	0%	1%	1%	1%	0%	0%	0%	0%	3%	0%	0%	1%	0%	1%	1%
Barge Transport	0%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
Electrical Infrastructure	**2%**	**2%**	**3%**	**2%**	**2%**	**3%**	**3%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**2%**	**3%**	**2%**	**3%**
Offshore Converterstation	2%	2%	2%	1%	2%	2%	2%	2%	2%	1%	1%	1%	1%	1%	1%	2%	1%	2%
Onshore Substation	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	1%	1%	1%
Export Cabling	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Inter-array Cabling	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Table 37: Scenario 1: 25-year Lifetime Environmental Impact Results

Domain	GWP	TAP	ODP	ALO	ULO	NLT	FDP	MDP	WDP	FET	MET	TET	HT	FEP	MEP	IR	PMF	POF
Offshore Turbine	**5.67E+00**	**1.88E-02**	**8.81E-09**	**3.98E-04**	**3.03E-03**	**1.09E-06**	**1.55E+00**	**3.95E+00**	**2.76E-05**	**1.24E+00**	**1.09E+00**	**9.83E-04**	**5.20E+00**	**4.83E-03**	**1.18E-02**	**2.83E-01**	**1.10E-02**	**1.91E-02**
Support Structure	3.85E+00	1.18E-02	6.25E-09	2.10E-04	1.87E-03	7.47E-07	1.01E+00	2.56E+00	1.93E-05	3.54E-01	3.22E-01	6.18E-04	2.43E+00	2.71E-03	5.01E-03	1.95E-01	6.87E-03	1.23E-02
Foundation	2.28E+00	6.90E-03	3.68E-09	1.28E-04	1.10E-03	4.36E-07	6.01E-01	1.54E+00	1.15E-05	2.08E-01	1.87E-01	3.69E-04	1.44E+00	1.61E-03	2.96E-03	1.16E-01	4.04E-03	7.24E-03
Tower	9.96E-01	3.17E-03	1.63E-09	5.34E-05	4.84E-04	1.89E-07	2.62E-01	6.28E-01	4.85E-06	6.30E-02	8.09E-02	1.56E-04	5.53E-01	6.91E-04	1.29E-03	5.05E-02	1.85E-03	3.19E-03
Transition Piece	5.67E-01	1.72E-03	9.20E-10	3.18E-05	2.77E-04	1.09E-07	1.47E-01	3.85E-01	2.89E-06	3.15E-02	4.80E-02	8.61E-05	3.63E-01	4.03E-04	7.40E-04	2.85E-02	9.24E-04	1.81E-03
Scour Protection	8.15E-03	3.95E-05	1.51E-11	3.02E-07	5.67E-06	1.25E-08	2.53E-03	7.30E-04	3.87E-08	3.15E-02	2.45E-04	6.41E-07	3.02E-03	3.70E-06	1.96E-05	2.70E-04	2.12E-05	2.48E-04
Rotor Nacelle Assembly	1.81E+00	6.92E-03	2.57E-09	1.88E-04	1.19E-03	3.44E-07	5.43E-01	1.39E+00	8.32E-06	8.63E-01	7.68E-01	3.65E-04	2.77E+00	2.12E-03	6.77E-03	8.78E-02	4.09E-03	6.86E-03
Nacelle	1.06E+00	4.57E-03	1.84E-09	7.20E-05	9.04E-04	2.86E-07	2.94E-01	1.12E+00	6.72E-06	7.38E-01	7.47E-01	3.10E-04	2.50E+00	1.91E-03	5.73E-03	7.24E-02	2.74E-03	4.62E-03
DDPMG	6.73E-01	3.11E-03	1.26E-09	5.40E-05	7.10E-04	2.26E-07	1.79E-01	7.43E-01	5.14E-06	7.25E-01	6.30E-01	2.41E-04	2.05E+00	1.58E-03	5.18E-03	5.70E-02	1.69E-03	3.24E-03
Yaw Mechanism	1.39E-01	6.09E-04	2.01E-10	4.50E-06	8.38E-05	2.33E-08	3.73E-02	2.11E-01	6.81E-07	3.41E-02	5.48E-02	3.05E-05	1.84E-01	1.72E-04	2.96E-04	6.13E-03	4.99E-04	5.58E-04
Base Plate	9.89E-02	3.72E-04	1.77E-10	4.50E-06	3.71E-05	2.17E-08	3.34E-02	7.05E-02	5.62E-07	3.65E-03	2.99E-02	2.52E-05	1.69E-01	8.34E-05	1.39E-04	5.40E-03	2.28E-04	3.90E-04
Nacelle Cover	9.89E-02	3.06E-04	1.11E-10	0.00E+00	3.19E-05	5.30E-09	2.64E-02	6.41E-02	3.27E-07	5.90E-03	2.74E-02	5.27E-06	9.21E-02	2.62E-05	1.35E-04	2.05E-03	1.59E-04	2.79E-04
Direct-Drive Shaft	3.87E-02	1.64E-04	4.77E-11	9.29E-06	1.48E-05	4.89E-09	1.03E-02	2.74E-02	1.39E-07	0.00E+00	5.83E-03	7.66E-06	2.86E-02	2.09E-05	5.34E-05	1.46E-03	1.60E-04	1.34E-04
Rotor	7.39E-01	2.35E-03	7.27E-10	1.17E-04	2.72E-04	5.61E-08	2.43E-01	2.76E-01	1.56E-06	2.84E-02	2.70E-02	5.51E-05	2.78E-01	2.13E-04	1.04E-03	1.59E-02	1.35E-03	2.23E-03
Blades	5.41E-01	1.59E-03	4.75E-10	1.04E-04	1.69E-04	2.26E-08	1.92E-01	2.69E-01	4.95E-07	6.79E-03	5.76E-03	1.32E-05	7.42E-02	1.67E-04	7.79E-04	9.00E-03	6.67E-04	1.45E-03
Hub	2.04E-01	7.63E-04	2.51E-10	1.35E-05	1.02E-04	3.36E-08	3.60E-02	7.11E-03	1.07E-06	2.16E-02	2.13E-02	4.20E-05	2.02E-01	1.11E-04	2.58E-04	6.91E-03	6.83E-04	7.78E-04
Assembly	3.78E-03	2.03E-06	1.17E-12	6.65E-07	2.19E-07	1.11E-09	1.57E-03	5.02E-05	3.45E-08	1.79E-05	1.96E-05	9.14E-08	5.00E-04	1.88E-07	1.20E-06	8.69E-06	1.11E-06	3.69E-06
Operation & Maintenance	**4.81E-01**	**3.47E-03**	**8.49E-10**	**4.18E-05**	**4.84E-04**	**1.49E-07**	**1.28E-01**	**1.29E+00**	**4.19E-06**	**1.84E+00**	**1.59E+00**	**1.15E-04**	**3.75E+00**	**3.29E-03**	**2.38E-03**	**2.63E-02**	**1.56E-03**	**3.82E-03**
Part Replacement	3.26E-01	0.00E+00	6.48E-10	3.60E-05	3.71E-04	1.10E-07	7.20E-02	1.07E+00	3.64E-06	1.52E+00	1.31E+00	9.95E-05	3.11E+00	2.72E-03	2.13E-03	2.37E-02	1.33E-03	3.15E-03
Cable Replacement	6.51E-02	0.00E+00	0.00E+00	5.50E-06	5.50E-05	1.80E-08	2.12E-02	2.13E-01	5.39E-07	3.24E-01	2.79E-01	1.12E-05	6.42E-01	5.00E-04	2.39E-04	1.90E-03	2.08E-04	5.41E-04
S.S. Oil Replacement	6.51E-02	0.00E+00	0.00E+00	2.66E-07	3.71E-05	1.37E-08	1.80E-02	2.87E-04	9.73E-09	2.69E-04	2.34E-04	2.97E-06	2.55E-03	2.50E-06	6.83E-06	5.12E-04	9.09E-06	1.12E-04
Helicopter Transport	0.00E+00	0.00E+00	0.00E+00	2.96E-08	2.20E-06	1.37E-08	1.80E-02	0.00E+00	2.16E-09	0.00E+00	0.00E+00	6.95E-07	1.28E-03	6.25E-07	3.42E-06	9.31E-05	5.59E-06	1.07E-05
Freight Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.38E-09	1.35E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.90E-07	0.00E+00	0.00E+00	2.05E-06	7.75E-05	4.20E-06	6.68E-06
Barge Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.40E-10	9.03E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.37E-06	5.17E-06	6.99E-07	4.01E-06
Installation	**1.25E-01**	**4.46E-04**	**5.35E-10**	**9.69E-06**	**6.59E-05**	**6.06E-08**	**4.67E-02**	**1.28E-01**	**8.09E-07**	**6.68E-02**	**5.83E-02**	**7.03E-05**	**4.34E-02**	**1.97E-04**	**2.53E-04**	**8.06E-03**	**2.39E-04**	**7.30E-04**
Freight Transport	9.23E-02	2.50E-04	4.12E-10	6.51E-06	5.19E-05	3.33E-08	3.57E-02	5.37E-02	3.27E-07	4.17E-02	3.65E-02	6.79E-05	3.84E-02	8.34E-05	1.80E-04	5.45E-03	1.36E-04	4.50E-04
Barge Transport	3.66E-02	1.96E-04	1.23E-10	3.09E-06	1.40E-05	2.73E-08	1.10E-02	4.08E-02	3.27E-07	1.98E-02	1.73E-02	2.33E-06	5.03E-03	8.34E-05	1.48E-04	2.58E-03	1.03E-04	2.79E-04
Decommissioning	**7.26E-02**	**2.63E-04**	**2.96E-10**	**7.04E-08**	**3.64E-05**	**3.50E-08**	**2.59E-02**	**2.83E-03**	**6.95E-09**	**4.41E-03**	**3.80E-03**	**3.74E-05**	**2.35E-02**	**7.70E-06**	**1.53E-04**	**0.00E+00**	**1.37E-04**	**4.34E-04**
Freight Transport	4.79E-02	2.63E-04	2.18E-10	1.45E-08	2.75E-05	1.76E-08	1.89E-02	5.70E-04	1.34E-09	8.33E-04	7.17E-04	3.59E-05	2.03E-02	1.47E-06	1.14E-04	4.42E-06	7.21E-05	2.86E-04
Barge Transport	2.32E-02	0.00E+00	7.81E-11	1.24E-06	8.91E-06	1.74E-08	7.02E-03	5.03E-03	1.04E-07	1.27E-03	1.74E-03	1.48E-06	3.20E-03	1.42E-05	3.90E-05	0.00E+00	6.54E-05	1.48E-04
Electrical Infrastructure	**1.65E-01**	**5.57E-04**	**3.06E-10**	**7.58E-07**	**8.93E-05**	**3.51E-08**	**4.71E-02**	**2.82E-03**	**5.31E-08**	**8.70E-04**	**1.37E-03**	**2.47E-05**	**1.94E-01**	**8.61E-06**	**2.36E-04**	**2.55E-03**	**3.01E-04**	**6.72E-04**
Offshore Converterstation	6.51E-02	2.35E-04	2.07E-10	4.81E-07	3.71E-05	2.36E-08	3.17E-02	2.22E-03	5.13E-08	4.01E-04	3.71E-04	1.67E-05	1.27E-01	5.56E-06	1.58E-04	1.04E-03	1.32E-04	4.50E-04
Onshore Substation	6.51E-02	1.76E-04	9.81E-11	7.07E-07	2.85E-05	1.12E-08	1.50E-02	2.90E-03	6.09E-08	7.16E-04	9.61E-04	7.90E-06	5.96E-02	8.09E-06	7.47E-05	2.01E-03	9.58E-05	2.13E-04
Export Cabling	6.51E-02	8.19E-06	9.11E-13	4.01E-07	6.72E-07	2.39E-10	3.09E-04	1.49E-03	3.37E-08	4.60E-04	7.25E-04	1.12E-07	8.52E-03	4.55E-06	3.00E-06	1.35E-03	2.72E-06	7.29E-06
Inter-array Cabling	8.35E-04	1.38E-06	1.87E-13	3.06E-07	1.34E-07	4.37E-11	4.71E-05	1.41E-03	2.72E-08	2.55E-04	2.36E-04	5.39E-08	1.83E-03	3.54E-06	5.68E-07	6.64E-04	5.40E-07	1.44E-06
Total	**6.51E+00**	**2.35E-02**	**1.08E-08**	**4.50E-04**	**3.71E-03**	**1.37E-06**	**1.80E+00**	**5.37E+00**	**3.27E-05**	**3.15E+00**	**2.74E+00**	**1.23E-03**	**9.21E+00**	**8.34E-03**	**1.48E-02**	**3.20E-01**	**1.32E-02**	**2.48E-02**

Table 38: Scenario 2: 35-year Lifetime Environmental Impact Results

Domain	GWP	TAP	ODP	ALO	ULO	NLT	FDP	MDP	WDP	FET	MET	TET	HT	FEP	MEP	IR	PMF	POF
Offshore Turbine	**4.07E+00**	**1.36E-02**	**7.60E-09**	**2.50E-04**	**1.99E-03**	**7.89E-07**	**1.11E+00**	**2.86E+00**	**2.09E-05**	**7.98E-01**	**7.07E-01**	**4.40E-04**	**3.57E+00**	**3.28E-03**	**8.47E-03**	**2.18E-01**	**8.57E-03**	**1.37E-02**
Support Structure	2.77E+00	8.58E-03	5.39E-09	1.33E-04	1.22E-03	5.40E-07	7.25E-01	1.85E+00	1.46E-05	2.25E-01	2.08E-01	2.76E-04	1.67E+00	1.84E-03	3.60E-03	1.50E-01	5.37E-03	8.82E-03
Foundation	1.64E+00	5.00E-03	3.18E-09	7.97E-05	7.24E-04	3.15E-07	4.29E-01	1.12E+00	8.72E-06	1.35E-01	1.24E-01	1.65E-04	9.90E-01	1.09E-03	2.13E-03	8.93E-02	3.16E-03	5.19E-03
Tower	7.15E-01	2.30E-03	1.41E-09	3.36E-05	3.08E-04	1.37E-07	1.87E-01	4.55E-01	3.66E-06	5.68E-02	5.24E-02	6.96E-05	4.30E-01	4.68E-04	9.26E-04	3.84E-02	1.40E-03	2.29E-03
Transition Piece	4.09E-01	1.25E-03	7.94E-10	1.99E-05	1.81E-04	7.89E-08	1.07E-01	2.79E-01	2.18E-06	3.36E-02	3.11E-02	4.13E-05	2.48E-01	2.73E-04	5.32E-04	2.23E-02	7.90E-04	1.30E-03
Scour Protection	5.83E-03	2.83E-05	1.30E-11	2.00E-07	3.85E-06	9.03E-09	1.83E-03	5.88E-04	2.90E-08	2.69E-04	2.34E-04	2.85E-07	1.98E-03	2.49E-06	1.38E-05	2.06E-04	1.62E-05	3.92E-05
Rotor Nacelle Assembly	1.30E+00	5.02E-03	2.21E-09	1.17E-04	7.71E-04	2.49E-07	3.89E-01	1.01E+00	6.28E-06	5.73E-01	5.00E-01	1.63E-04	1.90E+00	1.44E-03	4.87E-03	6.74E-02	3.20E-03	4.92E-03
Nacelle	7.64E-01	3.31E-03	1.59E-09	4.37E-05	5.93E-04	2.07E-07	2.11E-01	8.06E-01	5.07E-06	5.54E-01	4.82E-01	1.39E-04	1.72E+00	1.29E-03	4.12E-03	5.52E-02	2.14E-03	3.32E-03
DDPMG	4.81E-01	2.25E-03	1.08E-09	2.97E-05	4.55E-04	1.64E-07	1.28E-01	5.39E-01	3.88E-06	4.80E-01	4.16E-01	1.08E-04	1.41E+00	1.07E-03	3.72E-03	4.36E-02	1.32E-03	2.32E-03
Yaw Mechanism	1.01E-01	4.41E-04	1.73E-10	5.83E-06	5.46E-05	1.68E-08	2.68E-02	1.51E-01	5.15E-07	4.60E-02	4.11E-02	1.36E-05	1.55E-01	1.17E-04	1.54E-04	4.72E-03	3.90E-04	4.01E-04
Base Plate	7.13E-02	2.69E-04	1.53E-10	3.85E-06	5.23E-05	1.57E-08	2.39E-02	5.00E-02	4.24E-07	2.21E-02	1.94E-02	1.13E-05	1.17E-01	7.42E-05	1.00E-04	4.15E-03	1.78E-04	2.79E-04
Nacelle Cover	6.94E-02	2.22E-04	9.58E-11	2.04E-06	2.08E-05	3.85E-09	1.89E-02	4.67E-02	1.15E-07	3.77E-03	3.74E-03	3.42E-06	1.98E-02	1.81E-05	9.66E-05	1.57E-03	1.25E-04	2.00E-04
Direct-Drive Shaft	2.79E-02	1.19E-04	4.11E-11	1.58E-06	1.00E-05	3.54E-09	7.40E-03	2.00E-02	1.05E-07	2.42E-03	2.34E-03	2.36E-06	1.71E-02	1.43E-05	3.79E-05	1.12E-03	1.25E-04	9.53E-05
Rotor	5.32E-01	1.70E-03	6.27E-10	7.27E-05	1.78E-04	4.07E-08	1.76E-01	1.99E-01	1.18E-06	1.83E-02	1.75E-02	2.47E-05	1.88E-01	1.44E-04	7.45E-04	1.22E-02	1.06E-03	1.60E-03
Blades	3.87E-01	1.15E-03	4.10E-10	6.29E-05	1.11E-04	2.43E-08	1.38E-01	1.94E-01	8.06E-07	4.31E-03	3.74E-03	5.91E-06	5.07E-02	6.92E-05	5.60E-04	6.92E-03	5.21E-04	1.04E-03
Hub	1.45E-01	5.53E-04	2.17E-10	9.76E-06	6.69E-05	1.63E-08	3.87E-02	5.29E-03	3.74E-07	1.40E-02	1.38E-02	1.88E-05	1.38E-01	7.48E-05	1.85E-04	5.32E-03	5.34E-04	5.59E-04
Assembly	2.59E-03	1.13E-06	1.00E-12	4.19E-07	0.00E+00	7.94E-10	1.13E-03	0.00E+00	2.56E-08	0.00E+00	0.00E+00	5.18E-08	6.59E-04	0.00E+00	8.62E-07	6.25E-06	7.06E-07	2.61E-06
Operation & Maintenance	**5.67E-01**	**4.29E-03**	**1.20E-09**	**4.25E-05**	**4.87E-04**	**1.76E-07**	**1.60E-01**	**1.56E+00**	**5.10E-06**	**2.02E+00**	**1.74E+00**	**7.90E-05**	**4.37E+00**	**3.79E-03**	**2.67E-03**	**3.18E-02**	**2.00E-03**	**4.65E-03**
Part Replacement	4.77E-01	3.50E-03	9.65E-10	3.65E-05	4.26E-04	1.46E-07	1.23E-01	1.30E+00	4.43E-06	1.66E+00	1.44E+00	6.92E-05	3.61E+00	3.13E-03	2.39E-03	2.87E-02	1.71E-03	3.83E-03
Cable Replacement	7.46E-02	7.29E-04	9.94E-11	5.59E-06	5.54E-05	2.15E-08	2.69E-02	2.58E-01	6.58E-07	3.55E-01	3.07E-01	7.77E-06	7.47E-01	6.52E-04	2.69E-04	2.30E-03	2.68E-04	6.58E-04
S.S. Oil Replacement	6.16E-03	3.05E-05	8.74E-11	2.79E-07	3.08E-06	5.62E-09	7.49E-03	5.88E-04	1.16E-08	2.69E-04	2.34E-04	1.48E-06	2.64E-03	2.49E-06	7.76E-06	6.18E-04	1.20E-05	1.36E-04
Helicopter Transport	5.19E-03	1.58E-05	2.51E-11	2.00E-08	1.54E-06	1.59E-09	1.74E-03	0.00E+00	2.32E-09	0.00E+00	0.00E+00	4.66E-07	1.32E-03	0.00E+00	2.59E-06	1.12E-04	4.94E-06	9.14E-06
Freight Transport	3.24E-03	6.79E-06	1.74E-11	0.00E+00	0.00E+00	1.16E-09	1.22E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.77E-08	0.00E+00	0.00E+00	1.72E-06	9.37E-05	4.24E-06	5.22E-06
Barge Transport	3.24E-04	2.26E-06	1.14E-12	0.00E+00	0.00E+00	1.83E-10	8.71E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.62E-07	6.25E-06	7.06E-07	3.92E-06
Installation	**9.11E-02**	**3.24E-04**	**4.61E-10**	**7.78E-07**	**4.31E-05**	**4.39E-08**	**3.35E-02**	**3.53E-03**	**7.90E-08**	**8.07E-04**	**1.17E-03**	**3.14E-05**	**2.96E-02**	**9.35E-06**	**1.82E-04**	**2.76E-03**	**1.87E-04**	**5.24E-04**
Freight Transport	6.48E-02	1.81E-04	3.55E-10	4.79E-07	3.38E-05	2.41E-08	2.56E-02	2.06E-03	3.95E-08	5.38E-04	9.35E-04	3.04E-05	2.64E-02	5.61E-06	1.29E-04	1.96E-03	1.07E-04	3.23E-04
Barge Transport	2.63E-02	1.43E-04	1.06E-10	2.99E-07	9.23E-06	1.98E-08	7.92E-03	1.47E-03	3.83E-08	2.69E-04	2.34E-04	1.04E-06	3.29E-03	3.74E-06	5.26E-05	8.06E-04	8.05E-05	2.00E-04
Decommissioning	**5.09E-02**	**1.90E-04**	**2.55E-10**	**4.39E-07**	**2.38E-05**	**2.53E-08**	**1.85E-02**	**2.06E-03**	**4.65E-08**	**5.38E-04**	**7.01E-04**	**1.67E-05**	**1.65E-02**	**5.61E-06**	**1.10E-04**	**1.55E-03**	**1.07E-04**	**3.12E-04**
Freight Transport	3.44E-02	1.15E-04	1.88E-10	2.59E-07	1.77E-05	1.28E-08	1.36E-02	1.18E-03	2.56E-08	2.69E-04	4.68E-04	1.61E-05	1.38E-02	3.12E-06	8.19E-05	1.04E-03	5.65E-05	2.05E-04
Barge Transport	1.65E-02	7.58E-05	6.74E-11	2.00E-07	6.15E-06	1.26E-08	5.05E-03	8.82E-04	2.09E-08	2.69E-04	2.34E-04	6.74E-07	1.98E-03	2.49E-06	2.85E-05	5.12E-04	5.09E-05	1.06E-04
Electrical Infrastructure	**1.16E-01**	**4.04E-04**	**2.64E-10**	**6.09E-06**	**5.85E-05**	**2.54E-08**	**3.38E-02**	**9.43E-02**	**6.11E-07**	**4.31E-02**	**3.76E-02**	**1.11E-05**	**1.34E-01**	**1.33E-04**	**1.70E-04**	**6.20E-03**	**2.36E-04**	**4.82E-04**
Offshore Converterstation	7.84E-02	2.69E-04	1.78E-10	4.09E-06	3.92E-05	1.71E-08	2.27E-02	6.23E-02	4.10E-07	2.69E-02	2.36E-02	7.46E-06	8.63E-02	8.61E-05	1.13E-04	4.19E-03	1.58E-04	3.23E-04
Onshore Substation	3.73E-02	1.28E-04	8.46E-11	1.94E-06	1.85E-05	8.12E-09	1.08E-02	2.97E-02	1.94E-07	1.29E-02	1.12E-02	3.52E-06	4.08E-02	4.12E-05	5.35E-05	1.99E-03	7.49E-05	1.53E-04
Export Cabling	6.48E-04	5.66E-06	7.80E-13	3.99E-08	7.69E-07	1.83E-10	2.61E-04	2.06E-03	5.81E-09	2.96E-03	2.57E-03	5.18E-08	5.93E-03	4.99E-06	1.72E-06	1.87E-05	2.12E-06	5.22E-06
Inter-array Cabling	0.00E+00	1.13E-06	1.60E-13	0.00E+00	0.00E+00	6.10E-11	0.00E+00	2.94E-04	1.16E-09	5.38E-04	4.68E-04	2.59E-08	1.32E-03	1.25E-06	0.00E+00	6.25E-06	7.06E-07	1.31E-06
Total	**4.89E+00**	**1.88E-02**	**9.78E-09**	**3.00E-04**	**2.60E-03**	**1.06E-06**	**1.36E+00**	**4.52E+00**	**2.67E-05**	**2.86E+00**	**2.49E+00**	**5.78E-04**	**8.12E+00**	**7.21E-03**	**1.16E-02**	**2.60E-01**	**1.11E-02**	**1.97E-02**

Table 39: Scenario 3: Improved Critical Raw Material Recycling Environmental Impact Results

Domain	GWP	TAP	ODP	ALO	ULO	NLT	FDP	MDP	WDP	FET	MET	TET	HT	FEP	MEP	IR	PMF	POF
Offshore Turbine	**5.53E+00**	**1.82E-02**	**7.44E-09**	**3.35E-04**	**2.74E-03**	**9.76E-07**	**1.51E+00**	**3.76E+00**	**2.50E-05**	**1.10E+00**	**9.70E-01**	**7.75E-04**	**4.75E+00**	**4.44E-03**	**8.05E-03**	**2.02E-01**	**9.85E-03**	**1.83E-02**
Support Structure	3.76E+00	1.15E-02	5.28E-09	1.90E-04	1.68E-03	6.68E-07	9.82E-01	2.44E+00	1.75E-05	2.43E-01	2.85E-01	4.87E-04	2.22E+00	2.49E-03	3.42E-03	1.40E-01	6.17E-03	1.18E-02
Foundation	2.22E+00	6.68E-03	3.11E-09	1.14E-04	9.98E-04	3.90E-07	5.81E-01	1.47E+00	1.05E-05	1.45E-01	1.70E-01	2.91E-04	1.32E+00	1.48E-03	2.02E-03	8.29E-02	3.63E-03	6.92E-03
Tower	9.72E-01	3.07E-03	1.38E-09	4.78E-05	4.25E-04	1.69E-07	2.54E-01	5.99E-01	4.40E-06	6.12E-02	7.17E-02	1.23E-04	5.73E-01	6.35E-04	8.80E-04	3.57E-02	1.61E-03	3.05E-03
Transition Piece	5.56E-01	1.67E-03	7.77E-10	2.84E-05	2.50E-04	9.75E-08	1.45E-01	3.67E-01	2.62E-06	3.63E-02	4.25E-02	7.28E-05	3.29E-01	3.70E-04	5.06E-04	2.07E-02	9.08E-04	1.73E-03
Scour Protection	7.86E-03	3.84E-05	1.27E-11	2.75E-07	5.45E-06	1.11E-08	2.43E-03	6.54E-04	3.50E-08	2.90E-04	2.52E-04	4.98E-07	2.82E-03	3.48E-06	1.36E-05	1.94E-04	1.92E-05	5.11E-05
Rotor Nacelle Assembly	1.76E+00	6.71E-03	2.17E-09	1.66E-04	1.06E-03	3.08E-07	5.26E-01	1.32E+00	7.53E-06	7.87E-01	6.85E-01	2.88E-04	2.53E+00	1.95E-03	4.62E-03	6.27E-02	3.67E-03	6.56E-03
Nacelle	1.04E+00	4.43E-03	1.55E-09	6.22E-05	8.17E-04	2.56E-07	2.86E-01	1.06E+00	6.09E-06	7.62E-01	6.61E-01	2.45E-04	2.28E+00	1.75E-03	3.92E-03	5.13E-02	2.46E-03	4.42E-03
DDPMG	5.79E-01	3.01E-03	1.06E-09	4.23E-05	6.27E-04	2.03E-07	1.74E-01	7.09E-01	4.65E-06	6.60E-01	5.70E-01	1.90E-04	1.87E+00	1.45E-03	3.54E-03	4.05E-02	1.52E-03	3.10E-03
Yaw Mechanism	1.37E-01	5.90E-04	1.70E-10	8.31E-06	7.52E-05	2.09E-08	3.62E-02	1.99E-01	6.17E-07	6.35E-02	5.64E-02	2.41E-05	2.07E-01	1.58E-04	1.46E-04	4.38E-03	4.48E-04	5.34E-04
Base Plate	9.68E-02	3.60E-04	1.49E-10	5.47E-06	7.20E-05	1.94E-08	3.24E-02	6.57E-02	5.09E-07	3.02E-02	2.64E-02	1.99E-05	1.54E-01	1.01E-04	9.49E-05	3.86E-03	2.04E-04	3.73E-04
Nacelle Cover	1.29E-01	2.96E-04	9.38E-11	2.90E-06	2.83E-05	4.75E-09	2.56E-02	6.15E-02	1.39E-07	5.22E-03	5.28E-03	6.03E-06	2.61E-02	2.43E-05	9.17E-05	1.47E-03	1.44E-04	2.68E-04
Direct-Drive Shaft	3.77E-02	1.59E-04	4.03E-11	2.23E-06	1.31E-05	4.37E-09	9.93E-03	2.62E-02	1.25E-07	3.19E-03	3.02E-03	4.15E-06	2.26E-02	1.95E-05	3.65E-05	1.05E-03	1.43E-04	1.29E-04
Rotor	7.23E-01	2.28E-03	6.14E-10	1.04E-04	2.44E-04	5.03E-08	2.39E-01	2.61E-01	1.42E-06	2.52E-02	2.39E-02	4.35E-05	2.51E-01	1.95E-04	7.08E-04	1.14E-02	1.21E-03	2.14E-03
Blades	5.26E-01	1.54E-03	4.01E-10	8.96E-05	1.53E-04	2.02E-08	1.86E-01	6.87E-03	4.48E-07	6.09E-03	5.03E-03	1.04E-05	6.77E-02	9.38E-05	5.32E-04	6.43E-03	5.99E-04	1.39E-03
Hub	1.97E-01	7.39E-04	2.12E-10	1.39E-05	9.16E-05	3.01E-08	5.23E-02	2.55E-01	9.68E-07	1.91E-02	1.89E-02	3.31E-05	1.83E-01	1.01E-04	1.76E-04	4.94E-03	6.13E-04	7.45E-04
Assembly	3.72E-03	1.32E-06	9.95E-13	5.81E-07	0.00E+00	1.01E-09	1.55E-03	0.00E+00	3.16E-08	0.00E+00	0.00E+00	5.53E-08	7.05E-04	0.00E+00	1.04E-06	7.06E-06	7.37E-07	3.10E-06
Operation & Maintenance	**5.53E-01**	**4.10E-03**	**8.48E-10**	**4.32E-05**	**4.80E-04**	**1.57E-07**	**1.56E-01**	**1.47E+00**	**4.37E-06**	**1.98E+00**	**1.71E+00**	**1.00E-04**	**4.15E+00**	**3.66E-03**	**1.82E-03**	**1.80E-02**	**1.64E-03**	**4.43E-03**
Part Replacement	4.64E-01	3.34E-03	6.74E-10	3.72E-05	4.20E-04	1.29E-07	1.19E-01	1.23E+00	3.80E-06	1.63E+00	1.41E+00	8.71E-05	3.43E+00	3.03E-03	1.62E-03	1.62E-02	1.40E-03	3.65E-03
Cable Replacement	7.24E-02	6.96E-04	6.95E-11	5.69E-06	5.45E-05	1.90E-08	2.59E-02	2.43E-01	5.63E-07	3.49E-01	3.00E-01	9.79E-06	7.09E-01	6.31E-04	1.82E-04	1.30E-03	2.20E-04	6.27E-04
S.S. Oil Replacement	7.03E-03	2.91E-05	6.11E-11	2.75E-07	3.27E-06	4.94E-09	7.28E-03	3.27E-04	1.02E-08	2.90E-04	2.52E-04	2.60E-06	2.82E-03	2.78E-06	5.21E-06	3.50E-04	9.58E-06	1.30E-04
Helicopter Transport	5.79E-03	2.12E-05	2.46E-11	3.06E-08	2.18E-06	1.96E-09	2.32E-03	0.00E+00	2.26E-09	0.00E+00	0.00E+00	6.08E-07	1.41E-03	6.95E-07	2.61E-06	6.35E-05	5.90E-06	1.24E-05
Freight Transport	4.14E-03	9.26E-06	1.70E-11	0.00E+00	0.00E+00	1.46E-09	1.66E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.66E-07	0.00E+00	0.00E+00	1.56E-06	5.30E-05	4.42E-06	7.74E-06
Barge Transport	4.14E-04	2.65E-06	1.12E-12	0.00E+00	0.00E+00	2.53E-10	1.10E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.04E-06	3.53E-06	7.37E-07	4.64E-06
Installation	**1.24E-01**	**4.33E-04**	**4.52E-10**	**1.10E-06**	**5.89E-05**	**5.43E-08**	**4.54E-02**	**4.91E-03**	**9.48E-08**	**1.16E-03**	**1.51E-03**	**5.54E-05**	**3.95E-02**	**1.32E-05**	**1.73E-04**	**2.57E-03**	**2.15E-04**	**6.98E-04**
Freight Transport	8.81E-02	2.42E-04	3.48E-10	6.72E-07	4.69E-05	2.99E-08	3.47E-02	2.62E-03	4.85E-08	8.70E-04	1.26E-03	5.36E-05	3.53E-02	7.65E-06	1.22E-04	1.82E-03	1.22E-04	4.30E-04
Barge Transport	3.56E-02	1.90E-04	1.04E-10	4.28E-07	1.31E-05	2.44E-08	1.07E-02	1.96E-03	4.63E-08	2.90E-04	2.52E-04	1.82E-06	4.94E-03	4.87E-06	5.06E-05	7.45E-04	9.21E-05	2.68E-04
Decommissioning	**6.95E-02**	**2.54E-04**	**2.50E-10**	**6.42E-07**	**3.27E-05**	**3.13E-08**	**2.52E-02**	**2.62E-03**	**5.53E-08**	**5.80E-04**	**7.55E-04**	**2.95E-05**	**2.12E-02**	**7.65E-06**	**1.05E-04**	**1.44E-03**	**1.24E-04**	**4.15E-04**
Freight Transport	4.68E-02	1.53E-04	1.84E-10	3.67E-07	2.51E-05	1.58E-08	1.83E-02	1.31E-03	3.05E-08	2.90E-04	7.55E-04	2.84E-05	1.83E-02	4.17E-06	7.82E-05	9.64E-04	6.49E-05	2.74E-04
Barge Transport	2.28E-02	1.01E-04	6.59E-11	2.75E-07	7.63E-06	1.55E-08	6.84E-03	1.31E-03	2.48E-08	2.90E-04	2.52E-04	1.16E-06	2.82E-03	3.48E-06	2.66E-05	4.73E-04	5.90E-05	1.41E-04
Electrical Infrastructure	**1.58E-01**	**5.40E-04**	**2.58E-10**	**8.65E-06**	**8.07E-05**	**3.15E-08**	**4.58E-02**	**1.24E-01**	**7.33E-07**	**5.92E-02**	**5.16E-02**	**1.95E-05**	**1.79E-01**	**1.81E-04**	**1.61E-04**	**5.76E-03**	**2.71E-04**	**6.43E-04**
Offshore Converterstation	1.07E-01	3.60E-04	1.75E-10	5.84E-06	5.45E-05	2.11E-08	3.08E-02	8.21E-02	4.92E-07	3.71E-02	3.25E-02	1.32E-05	1.15E-01	1.17E-04	1.08E-04	3.89E-03	1.81E-04	4.30E-04
Onshore Substation	5.05E-02	1.71E-04	8.28E-11	2.75E-06	2.51E-05	1.00E-08	1.46E-02	3.89E-02	2.34E-07	1.77E-02	1.53E-02	6.25E-06	5.43E-02	5.56E-05	5.11E-05	1.85E-03	8.62E-05	2.04E-04
Export Cabling	8.28E-04	7.94E-06	7.71E-13	6.11E-08	1.09E-06	1.90E-10	3.31E-04	2.62E-03	6.77E-09	3.77E-03	3.27E-03	1.11E-07	7.76E-03	6.95E-06	2.08E-06	1.77E-05	2.21E-06	7.74E-06
Inter-array Cabling	0.00E+00	1.32E-06	1.49E-13	0.00E+00	0.00E+00	6.33E-11	0.00E+00	6.54E-04	1.13E-09	8.70E-04	7.55E-04	5.53E-08	1.41E-03	1.39E-06	5.21E-07	3.53E-06	7.37E-07	1.55E-06
Total	**6.43E+00**	**2.35E-02**	**9.25E-09**	**4.10E-04**	**3.39E-03**	**1.25E-06**	**1.78E+00**	**5.36E+00**	**3.03E-05**	**3.14E+00**	**2.73E+00**	**9.80E-04**	**9.14E+00**	**8.30E-03**	**1.03E-02**	**2.30E-01**	**1.21E-02**	**2.45E-02**