Life Cycle Assessment of Floating Offshore Wind Farms: The Case of Hywind Tampen in Norway

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Abstract: To address climate change and energy security issues from fossil fuels, wind power is a promising renewable energy source, projected to grow significantly by 2050. Offshore wind energy, especially floating offshore wind farms shows great potential due to higher and more consistent wind speeds at sea. However, these turbines have negative environmental burdens throughout their life cycle. This The present study focuses on a comprehensive cradle-to-grave life cycle assessment of the Hywind Tampen floating offshore wind farm in Norway. The assessment covers all stages from manufacturing, transportation, installation, operation, and maintenance to decommissioning, utilizing openLCA® software and ecoinvent 3.9 database with the ReCiPe 2016 impact assessment method. Key findings indicate that manufacturing is the primary contributor to total emissions, followed by operation and maintenance. The study emphasizes the necessity of developing more sustainable manufacturing methods, designing turbines that are more efficient and versatile, and better maintenance forecasting and planning in order to minimize the environmental impact of these turbines.

Keywords: life cycle assessment, offshore wind, floating, openLCA®, wind energy, renewable energy, climate change

1. INTRODUCTION

Rapid urbanization and population growth are driving a 50% increase in global energy demand in the coming years (Skår, 2022). This surge is primarily met by fossil fuels, leading to resource depletion, global warming, and other environmental impacts. Among renewable energy resources wind power stands out as one of the most accessible and environmentally friendly options (Narayanan, 2023). Additionally, offshore wind energy is emerging as one of the most promising options for the coming years and decades, thanks to the higher and more consistent wind speeds found in open seas(Kaltenborn et al., 2023).

Despite producing clean electricity, offshore wind turbines have environmental impacts across their life cycle, including manufacturing, installation, and decommissioning. The environmental impact and energy performance of offshore wind technology are commonly assessed using Life Cycle Assessment (LCA) (Bhandari et al., 2020) which is the most commonly employed method to simulate and assess the environmental impacts of products and processes (Barahmand and Eikeland, 2022).

Offshore wind turbines are categorized into two types based on their foundations (Bhattacharya, 2019).

Grounded (bottom-fixed): The wind turbine is securely bolted or driven into the seabed, like a giant anchor.

Floating: The wind turbine sits on a special platform that floats on the water, held in place by mooring lines.

Floating wind is an emerging technology, thus there is a limited availability of studies on the subject. After conducting a literature review, to date, the authors identified only 9 LCA studies on floating offshore wind. Although some studies like (Alsubal et al., 2021) were performed for life cycle cost assessment (LCCA). Among these studies only (Bang et al.,2019; Brussa et al., 2023; Garcia-Teruel et al., 2022; Struthers et al., 2023; Yildiz et al., 2021), were focused only on the floating platforms while the rest of them were more interested in bottom-fixed platforms.

Yildiz et al.(2021) conducted LCA on only one wind turbine. On the other hand, Bhandari (2020) conducted LCA on both farms and wind turbines, the rest of the studies was conducted on wind farms. The rest of the previous LCA studies were conducted on all life cycle stages of the wind farm including manufacturing, transportation, operation and maintenance (O&M) and decommissioning. On the other hand, Skår (2022) considered only the decommissioning stage. In all founded research, the manufacturing stage is regarded as the most important stage due to its highest contribution to the total emissions. Only a few studies conducted LCA on real-world wind farm case studies.

2. BACKGROUND

In recent years, the offshore wind industry has seen notable expansion, with offshore wind capacity growing by approximately 30% annually since 2010. Moreover, the size of the largest wind turbines has risen from 3 MW in 2010 to 8 MW in 2016, with projected ratings reaching up to 15–20 MW by 2030 (Garcia-Teruel et al., 2022).

While most deployed technologies utilize bottom-fixed structures such as monopiles or jackets, the utilization of floating turbines is rising as the industry explores locations with deeper sea depths. There's ongoing debate and research to determine the economic viability of floating platforms compared to bottom-fixed turbines, typically within the transition depth range of 50 to 100 meters. This threshold may be affected by factors such as the type of floater and the site conditions. However, for depths more than 100 meters, floating concepts are widely regarded as the most cost-effective approach (Karimirad, 2014). The floating wind turbine foundations can be categorized into three main types, as illustrated in Fig. 1 adopted from (Bhattacharya, 2019):

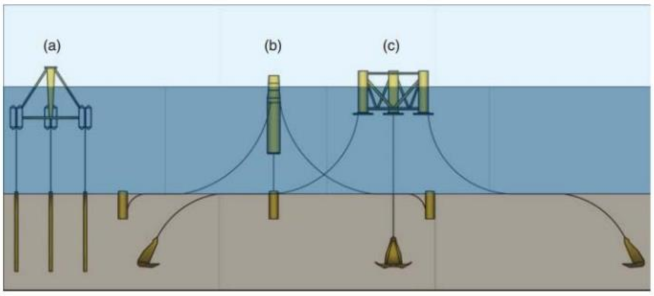


Fig. 1. The main Types of floating wind turbine adopted from (Bhattacharya, 2019).

1-TLP (Tension Leg Platform) with mooring stabilization: This system utilizes tensioned mooring for stability and is firmly anchored to the seabed to maintain buoyancy and stability.

2-Spar buoy with ballast stabilization, optionally equipped with motion control stabilizers: this system features a deep cylindrical base for ballast, with the lower section significantly heavier than the upper section, ensuring the center of buoyancy is higher than the center of gravity. While cost-effective initially, these structures require greater water depths and are not suitable for shallow environments.

3-Semisubmersible buoyancy stabilization: This design combines ballasting and tensioning principles, requiring substantial steel components.

3. METHODOLOGY

As per ISO 14040 and 14044 standards, the Life Cycle Assessment (LCA) framework comprises four stages (Lotfizadeh, 2024):

- Defining goals and scope
- Conducting a Life Cycle Inventory (LCI) analysis
- Performing a Life Cycle Impact Assessment (LCIA)
- Interpreting the results

3.1 Goal and scope

The initial step in an LCA, defining goals and scope, is widely regarded as crucial as it sets the research context, defines modelling requirements, and outlines project planning (Hesan, 2023).

The goals of this study were to: 1) Assessing the environmental impact of all life cycle stages of the Hywind Tampen wind farm. 2) Identifying the key elements affecting the environmental impact of offshore wind projects. 3) Learning about potential opportunities for environmental optimization throughout the life cycle and 4) Identifying relevant areas for further studies.

A cradle-to-grave method is chosen, and the boundaries of the system are shown Fig. 2. The defined functional unit (FU) in this study is 1 MWh of electricity generated by the wind farm during its life cycle and then delivered to the grid. Recycling was not included in the current study's end of life (EOL) stage due to uncertainties and data availability issues. As shown in Fig. 2, recycling falls outside the system boundaries.

3.2 Life cycle inventory analysis (LCI)

In this section the data collection and calculations will be briefly discussed. The Hywind Tampen is chosen as base case scenario because this wind farm uses the most recent technologies and largest turbine sizes in floating offshore wind (Lotfizadeh, 2024).

Table 1. Specifications of the base case (Lotfizadeh, 2024).

Wind Farm Name	Hywind Tampen
Distance to port	140 km
Power of each turbine	8 MW
Number of turbines	11
Wind Farm Capacity Factor	54 %
Generator type	Direct drive
Lifetime	20 years
Foundations	Concrete SPAR-type
Tower Length	92 m
Rotor Diameter	167 m
Total Height	175 m
Distance between the turbines	1.5 km
Water depth	200 m

Inventory analysis involves collecting data and performing calculations to identify the inputs and outputs of a product system. Inputs consist of energy, raw materials, and other products, while outputs encompass waste, water and air pollution, and various byproducts (Garcia-Teruel et al., 2022). These inputs and outputs were utilized as flows in each unit process and modelled using the openLCA® software. The inventory data were gathered from the following sources: 1) literature 2) reference wind turbines 3) environmental product declarations (EPDs).

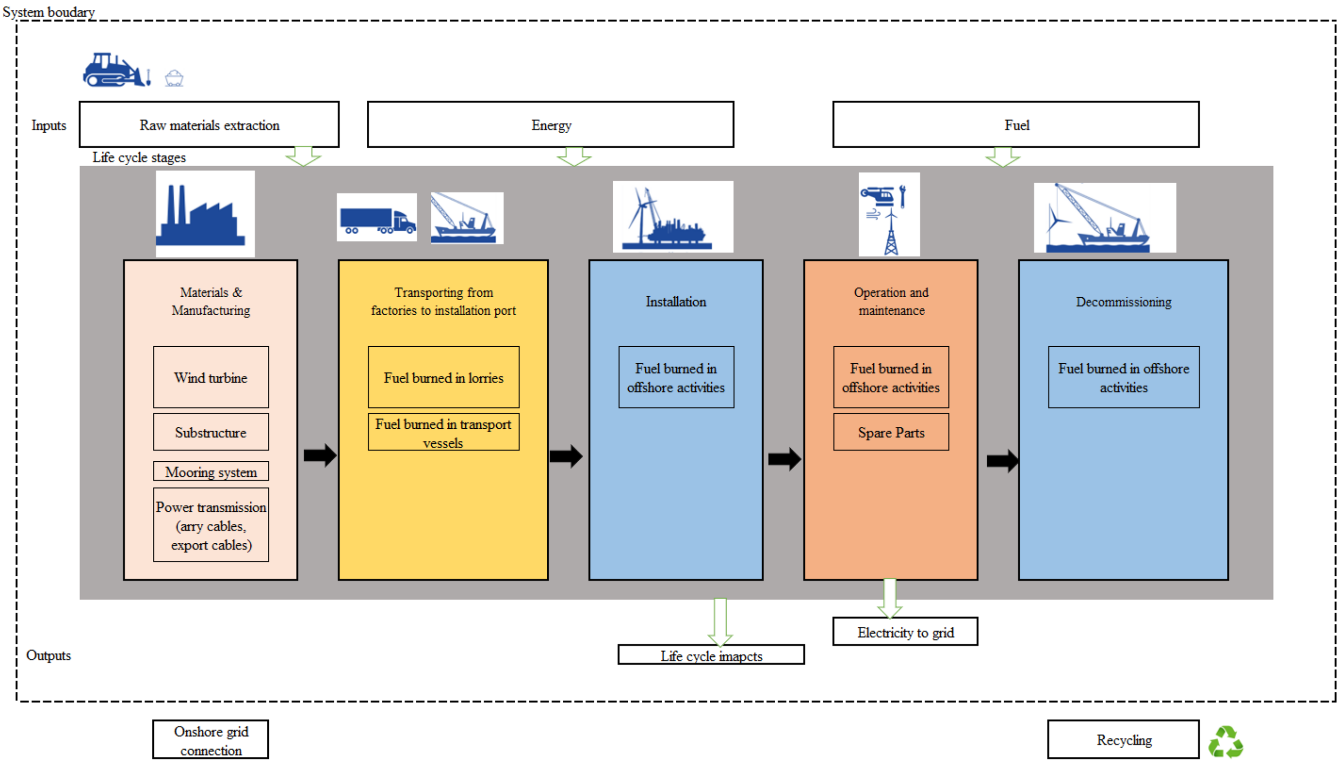


Fig. 2. System boundaries adopted from Lotfizadeh,2024)

It is important to note that access to specific details about wind turbines and wind farms is restricted due to commercial sensitivity. This lack of full transparency requires making certain assumptions when conducting LCA of offshore wind farms (Lotfizadeh, 2024).In the following a brief description of inventories and calculations will be given. Detailed inventories and calculations are available in open access ("Supplementary materials-life cycle assessment of offshore wind Farms, Lotfizadeh," 2024).

3.2.1 Materials and manufacturing

Simulating the raw material supply is done by using market datasets from the ecoinvent database, including material procurement and transit to Europe (Brussa et al., 2023). Previous research either focused on smaller wind turbines or lacked details about the materials used. Some studies like (Bang et al., 2019) and (Garcia-Teruel et al., 2022) estimated missing information by using regression. This study assumes a linear connection between the size of a turbine and material weight distribution. To determine the materials and weight for the 8 MW turbines , we used interpolation method based on a 6 MW turbine and a 15 MW reference turbine (Gaertner et al., 2020).

3.2.1.1 Tower and Nacelle

The main component of the 8 MW tower is low-alloy steel (Brussa et al., 2023). Siemens Gamesa EPD specifies the tower's length 92 meters, but information about its diameter and wall thickness is missing. The estimation of the weight was done using a linear interpolation method. The paint on the tower is negligible compared to the weight of other materials and was therefore excluded from the calculations.

For welding the processes "welding, arc, steel" in Ecoinvent was applied. In some other studies, the welding length was regarded as a continuous weld along the tower height. However, this study assumes that the tower is composed of welded segments, each with a height of 2 meters, and takes into account the peripheral length of these welded segments. Figure 3 illustrates the welding process, and Equation (1) demonstrates the calculation method.

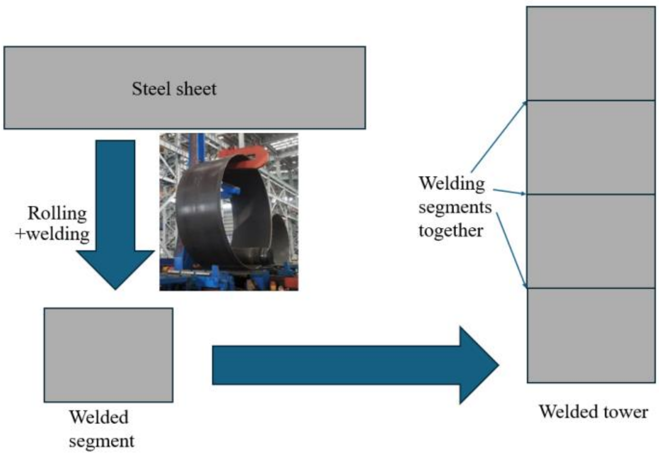


Fig. 3. Tower manufacturing process (Lotfizadeh, 2024).

$$L_W = L_T + N_s \times P \quad (1)$$

Where L_W represents the total welding length of the tower, L_T denotes the length of the wind turbine tower, N_s is the number of segments in the tower, and P is the perimeter of each segment. For an 8 MW wind turbine with a diameter of 10 m, the total welding length L_W is calculated as follows. The tower length is 92 m, made up of 46 segments, each 2 m in height and 10 m in diameter.

$$L_W = 92 + 46 \times \pi \times 10 = 1537\ m$$

3.2.1.2 Substructure

The material and weight of the 8 MW turbine substructure were taken from the environmental product declaration (EPD) of Siemens Gamesa 8 MW wind turbine. The substructure comprises two main components: the spar structure and ballast. The welding length of the spar structure was also calculated using Equation (1).

3.2.1.3 Mooring System

The mooring system data for the Hywind Tampen project was unavailable, however the weight and material data for the Hywind Scotland project were obtained from the project's manufacturing factsheets ("Manufacturing Factsheets," 2024). As a result, it was assumed that the mooring chains and anchors for the two projects were identical.

3.2.1.4 Power Transmission

The power transmission category includes inter-array cables, export cables, and substations. As Hywind Tampen wind farm distributes electricity to the nearby oil platforms, no substation was used in this study's base case scenario. Hywind Tampen inter-array and export cables were made by JDR company, which also manufactured cables for Hywind Scotland project, hence this study relied on the manufacturing factsheets of the Hywind Scotland project to get data on cable specifications. The Hywind Tampen Inter-array cables are 2.5 kilometres long, 66kV dynamic array cables (Lotfizadeh, 2024). The length of the export cable for the Hywind Tampen wind farm was determined to be 45.4 kilometers based on the relative distances of the five nearby platforms.

3.2.2 Transportation

Two modes of transportation are covered within the study's boundaries. To begin, as previously stated, this study models the raw material supply chain by using market datasets from the Ecoinvent database, which includes both material acquisition and transit to Europe (Brussa et al., 2023).Second, transportation from the factory to the installation port. These transports are carried out by truck or vessel. It was assumed that some parts of the turbine components were transported by truck within Denmark to the Siemens Gamesa factory and after assembling there were transported by ship to Norway to be installed at the Hywind Tampen site.

3.2.2 Installation

Most prior research used the "transport, freight, sea, ferry - GLO" process in ecoinvent to model the emissions from vessel installation activities; however, this study chose ecoinvent's "diesel, burned in diesel-electric generating set" process.

The energy demand of all vessels in installation activities including, installing foundations, turbine tower, rotor, nacelle, cables and mooring system was calculated and set as "diesel, burned in diesel-electric generating set" process in the openLCA® software.

3.2.3 Operation and Maintenance (O&M)

This stage quantifies emissions from operations and maintenance (O&M) activities, including unexpected repairs due to failures, routine preventative maintenance, and spare parts. It is important to note that due to the lack of data on remotely operated vehicles (ROVs) in the Ecoinvent database, their activities and emissions were excluded from this study.

3.2.3.1 Unexpected Maintenance

For unexpected maintenance the failure rates are categorized into major replacement, major repair, and minor repair. To calculate the overall number of turbine failures over their lifetime, the annual failure rates (Fig. 4) were multiplied by the number of turbines of the farm (×11×20). The time needed to fix each component within each operation and maintenance category were obtained from (Centeno-Telleria et al., 2024). With available energy consumption data for the vessels, the energy consumed for transport to the site and O&M operation was calculated in MWh using repair hours for each component. These figures were employed in ecoinvent's "diesel, burned in diesel-electric generating set" process in openLCA® software, following the same approach as the installation phase.

3.2.3.2 Regular Maintenance

The same method applied to regular maintenance, assuming once-a-year visit of the wind farm for preventative maintenance (PM) of the wind turbines' components.

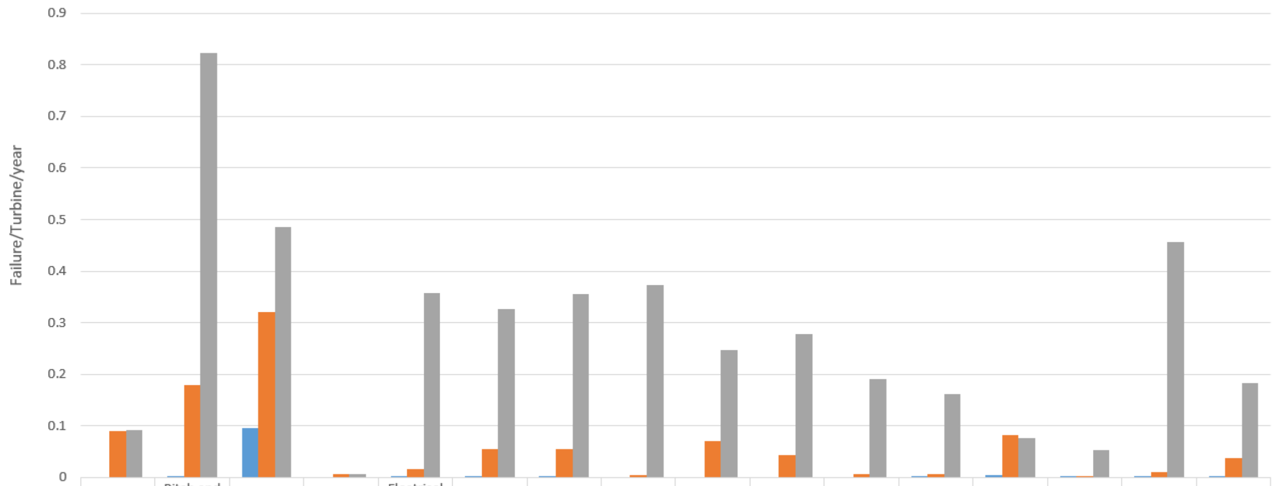
3.2.3.3 Spare parts

There is limited publicly available data on wind turbine component replacement rates. This study adopted the same exchange rate as (Arvesen et al., 2013).The rate of annual replacement for large wind turbine components is assumed to be 0.075 per wind turbine, and for generators and blades 0.333 per wind turbine.

Table 2. Spare parts replacement rates (Lotfizadeh, 2024).

Spare Parts	Annual replacement Per Wind Turbine	Annual replacement Per Wind Farm	Lifetime replacement Per Wind Farm
Replacement large parts[1]	0.075	0.825	16.5
Blades	0.333	3.667	73.3
Generators	0.333	3.667	73.3

[1] Turret / Nose, Bedplate, Flange, Shaft Bearings, Yaw System



	Tower	Pitch and Hydraulic system	Generator	Grease , oil	Electrical components	Contactor	Controls	Safety	Sensors	Pumps and Motors	Heaters, Coolers	Yaw system	Power converter	Transformer	Blades	Hub
Major replacement	0	0.001	0.095	0	0.002	0.002	0.001	0	0	0	0	0.001	0.005	0.001	0.001	0.001
Major repair	0.089	0.179	0.321	0.006	0.016	0.054	0.054	0.004	0.07	0.043	0.007	0.006	0.081	0.003	0.01	0.038
Minor repair	0.092	0.824	0.485	0.006	0.358	0.326	0.355	0.373	0.247	0.278	0.19	0.162	0.076	0.052	0.456	0.182

Fig. 4. Annual failure rates (Lotfizadeh, 2024).

3.2.4 Decommissioning

In this study it is assumed that the emissions from decommissioning stage are the reverse and equivalent to the installation stage.

3.2.4 Electricity delivered to the grid by the wind farm

The lifetime electricity production of the wind farm was calculated using the Equation 2.

$$E_{F,L,R} = C \times C_F \times L \times N_T - E_{Loss} \qquad (2)$$

where, each term is described in Table 3.

Table 3. Different terms of electricity calculation equation

Term	Description	Unit
$E_{F,L,R}$	Real power production of the farm after losses	MWh
C	Capacity of each turbine	MWh
C_F	Capacity factor	-
L	Lifetime of the wind farm	hour
N_T	Number of turbines in the farm	-
E_{Loss}	Electrical loss due to downtime	MWh

The loss due down time was calculated to be : $E_{Loss} =$ 53,508

Then

$$E_{F,L,R} = 8 \times 0.54 \times 20 \times 365 \times 24 \times 11 - 53508 = 8{,}256{,}878\ MWh$$

3.3 Life Cycle Impact Assessment (LCIA)

The openLCA® version 2.1 and ecoinvent 3.9 databases were utilized to perform LCIA. The ReCiPe 2016 v1.03 midpoint (H) method was selected to ensure that the results are comparable with previous studies.

4. RESULTS AND DISCUSSION

The impacts of the base case scenario were measured using the ReCiPe Midpoint (H) 2016 approach, which included 18 impact categories. The results were normalized by dividing by $E_{F,L,R}$ (the lifetime electrical power delivery of the farm after all losses in MWh). The results of the 18 impact categories of the base case scenario are shown in Table 5.

Some heatmaps were created using Microsoft Excel® software to help visualizing the data. These heatmaps employ three colors to depict varying levels of influence. Green colors indicate lesser impact values, yellow indicates the 50th percentile (the midpoint), and red intensifies when values exceed the middle and approach maximum impact. Fig. 5 illustrates the rule for creating heatmaps in Microsoft Excel®.

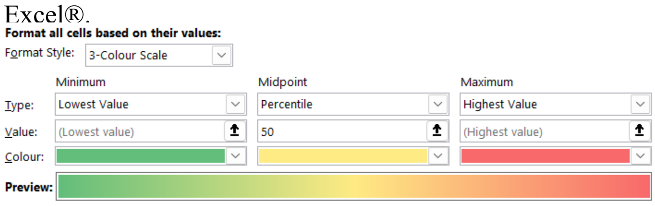


Fig. 5. The rule for creating heatmaps with Microsoft Excel®.

Table 4.A heatmap of the contribution of each life cycle stage to the total GWP for the base case scenario.

Stage	Contribution (%)	GWP (kg CO2-Eq/ MWh)
Wind Turbine Manufacturing	26.79%	9.85
Substructure Manufacturing	26.73%	9.83
Mooring system Manufacturing	2.82%	1.04
Power Transmission Manufacturing	1.32%	0.49
Transportation	0.07%	0.03
Installation	5.91%	2.17
O & M vessel	16.27%	5.98
O & M spare parts	14.18%	5.22
Decommissioning	5.91%	2.17
Total	100.00%	36.78

Transportation has a very low share, with 0.03 Kg CO_2-Eq per MWh. Manufacturing contributes the most to overall GWP, and the floating farm's substructure had significant emissions due to the use of concrete to manufacture the spar substructure. Figure 6 illustrates the contribution of the main five life cycle stages to the total GWP. The second contributor to the total GWP emissions was operation and maintenance stage.

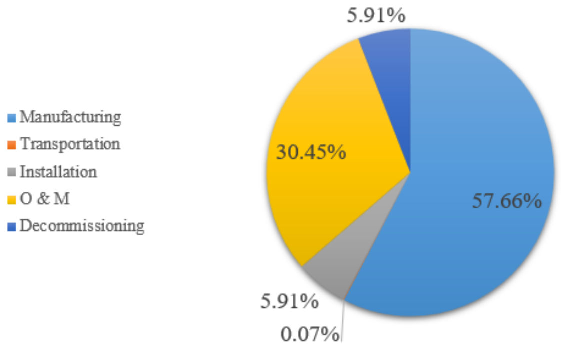


Fig. 6. Contribution of the main five life cycle stages to the total GWP.

4.1 Sensitivity Analysis

This section examines how variations in critical characteristics during the life cycle stages of the base case scenario impacts the overall results of the life cycle assessment.
As can be seen in Fig. 7 by decreasing the capacity factor (CF), it was expected that the global warming potential (GWP) and other environmental impacts would increase, which the results confirmed. Conversely, increasing the CF was expected to reduce GWP and other environmental impacts, and extending the farm's operational lifespan was anticipated to further decrease these impacts. Both hypotheses were validated by the results.
As the distance to the shore increases, the fuel consumption for vessel activities rises, leading to an increase in the GWP amount. However, the increase in GWP due to changes in the capacity factor (CF) and lifetime was significantly greater than the increase resulting from changes in distance to shore.
The strategy of towing to the shore was assumed to be used only for major replacements. While major repairs and minor repairs were conducted at the wind farm location. Results indicated that GWP increased by 11.5% when this strategy was implemented. Therefore, the optimal O&M approach for major replacements is to perform operations at the wind farm site rather than towing the wind turbines back to shore.

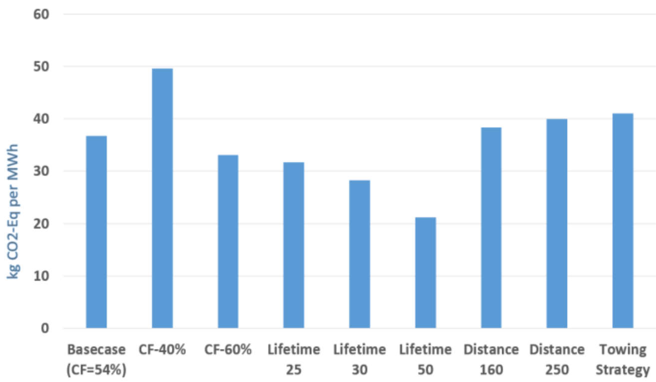


Fig. 7. An overview of GWP value in all scenarios.

5. CONCLUSIONS AND FURTHER RESEARCH

This paper provides a detailed assessment of the environmental implications associated with the Hywind Tampen floating offshore wind farm. The LCA findings indicated that, for the base case scenario, the GWP was calculated to be 36.78 kg CO_2-Eq per MWh.

It was also discovered that the manufacturing stage was accounted for nearly 57% of total GWP emissions, followed closely by the operation and maintenance (O&M) stage. Wind turbine failures accounted for approximately 90% of emissions throughout the operation and maintenance stage. To address these challenged wind turbine component manufacturers ought to develop and implement more sustainable production practices. For example, design strategies that maximize generation capacity per unit of material used could significantly reduce emissions associated with the manufacturing stage. Furthermore, improving wind turbine reliability can lower the environmental impact of the operation and maintenance stage.
Additionally,The sensitivity analysis explored how various parameters impact the results. Notably, the capacity factor and lifetime of the wind farm significantly influence overall environmental impacts.
Fort further studies, it is recommanded that:

- Using eco-friendly vessels during installation, operation and manintenance and decommissioning
- The O&M stage was shown to be the second-largest contributor to overall emissions in the evaluated wind farm. This emphasizes the significance of performing a sensitivity analysis for failure rates.

- Emissions from decommissioning were assumed to be equal to those from the installation stage. Further investigation of the decommissioning stage, as well as a sensitivity analysis using various decommissioning strategies, is recommended.
- The study did not include recycling in the end of life stage due to uncertainties and data availability issues. Further investigations on this stage, such as performing a cradle-to-cradle LCA, could provide useful insights into the materials used to manufacture offshore wind turbines.

Table 5. The results of 18 impact categories of the base case scenario

Impact category	Reference unit/MWh	Value
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO_2-Eq	0.15
climate change - global warming potential (GWP100)	kg CO_2-Eq	36.78
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg1,4-DCB-Eq	2.93
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg1,4-DCB-Eq	3.90
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	305.75
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	8.75
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.01
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.01
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	15.89
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	46.71
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.01
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.72
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	71.09
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	0.00
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.08
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.21
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.21
water use - water consumption potential (WCP)	m3	0.23

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