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Process Technology

Life Cycle Assessment of Offshore Wind Farms – A Comparative Study of Floating Vs. Fixed Offshore Wind Turbines

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Summary:

To address climate change and energy security issues associated with fossil fuels, new power generation methods such as renewable energy sources as a sustainable alternative for electricity generation are introduced. One of the most available and environmentally friendly renewable energy sources is wind power. Wind energy is expected to grow ninefold by 2050, accounting for 11% of total primary energy consumption worldwide. Within the domain of wind energy, offshore wind energy appears to be the most promising in the years ahead due to higher and steadier wind speeds in open seas. However, despite producing clean electricity during operation, offshore wind turbines have environmental impacts throughout upstream and downstream life cycle stages such as manufacturing, installation, and decommissioning. Offshore wind technology's environmental impact and energy performance can be measured, and the most commonly used assessment method is life cycle assessment (LCA). Nevertheless, after performing a scoping literature review method, it was observed that comprehensive assessments of the environmental impacts of different offshore wind technologies are limited. This study aims to bridge this gap by conducting a comprehensive cradle-to-grave LCA of two real case scenarios: floating (FOWF) and bottom fixed offshore wind farms (BFOWF), specifically Hywind Tampen and Dogger Bank. It encompasses all stages from manufacturing, transportation, installation, operation, and maintenance (O&M), and decommissioning. The methodology employed utilizes openLCA® software and ecoinvent 3.9 databases, with the ReCiPe 2016 v1.03 midpoint (H) impact assessment method. Key findings indicate that the environmental impact of Hywind Tampen FOWF is higher compared to Dogger Bank BFOWF, with sensitivity analysis revealing significant influences of capacity factor and lifetime of the wind farm. Among the life cycle stages analyzed, manufacturing emerges as the primary contributor to total emissions, with the O&M stage following closely behind. Consequently, this study underscores the critical need for the implementation of more sustainable manufacturing methods. One solution could be designing turbines with greater generation capacity to minimize material usage. Maintaining material usage at current levels for larger wind turbines could result in a significant decrease in emissions. Finally, the reliability of wind turbines needs to increase to reduce the share of O&M. Having said that this study also compares the emissions from the two studied offshore wind farms with other renewable and non-renewable energy sources, and although there are some environmental impacts associated with the offshore wind farms, they still could be one of the best alternatives for fossil fuels and some other renewable energy sources.

Preface

Conducting a comprehensive LCA is a meticulous endeavour, demanding rigorous data collection and analysis. Sourcing reliable data proved particularly challenging due to business confidentiality constraints. Fortunately, I was not alone in navigating these hurdles. I am deeply grateful for the unwavering support of my mentors and friends who illuminated the path forward.

Foremost, I extend my deepest appreciation to my supervisor, Dr. Hadi Amlashi, whose expertise, patience, and guidance have been instrumental in shaping this research. Dr. Amlashi's invaluable feedback and dedication to fostering academic growth have served as a constant source of motivation.

Additionally, I express sincere gratitude to my friend, Zahir Barahmand, Ph.D. researcher fellow at the University of South-Eastern Norway (USN). Zahir's encouragement and camaraderie have enriched this academic journey significantly. His remarkable scholarly contributions in literature review and LCA have greatly influenced my research.

I extend heartfelt thanks to my dear family, especially my beloved sister, Eli, whose unwavering encouragement, support, and boundless love have propelled me forward on this journey.

This work is dedicated to those who illuminate the path toward a greener future, to our precious Mother Nature, and every individual contributing to positive change.

Porsgrunn, May 10, 2024

Omid Lotfizadeh

Contents

Nomenclature

Symbol or Abbreviation	**Description**	**Unit**
AHTS	Anchor Handling Tug Supply Vessel	-
BFOW	Bottom-Fixed Offshore Wind Farm	-
BFWT	Bottom-Fixed Offshore Wind Turbine	-
C	Capacity of each turbine	MW
CF	Capacity Factor	-
CLV	Cable Laying Vesse	-
CML	Centre for Environmental Studies	-
DP	Dynamic Positioning	-
DNV	Det Norske Veritas	-
$E_{T,A}$	Annual electricity production of each turbine	MWh
$E_{T,L}$	Lifetime electricity production of each turbine	MWh
$E_{F,L}$	Lifetime electricity production of each Farm	MWh
E_{Loss}	Electrical loss of the farm due to downtime	MWh
$E_{F,L,R}$	Lifetime electrical power delivery of the farm after all losses	MWh
EPD	Environmental Product Declaration	-
EPS	Environmental Priority Strategies	-
EOL	End of Life	-
FU	Functional Unit	-
FOWF	Floating Offshore Wind Farm	-
FWT	Floating Wind Turbine	-
GWP	Global Warming Potentia	kg CO_2-Eq
HLV	Heavy Lift Vessel	-
HV	High-Voltage	V

Symbol or Abbreviation	**Description**	**Unit**
IMPACT	Integrated Methodology for Impact Assessment of Chemicals	-
IRENA	International Renewable Energy Agency	-
LCA	Life Cycle Assessment	-
LCIA	Life Cycle Impact Assessment	-
LCI	Life Cycle Inventory Analysis	-
LCOE	Levelized Cost of Energy	-
LCIA	Life Cycle Impact Assessment	-
L_W	The total welding length of the wind turbine tower	m
L_T	The length of the wind turbine tower	m
MV	Medium-Voltage	V
N_s	The number of welded segments of each turbine tower	-
O & M	Operation and Maintenance	-
OSV	Offshore Support Vessel	-
OWF	Offshore Wind Farm	-
OWT	Offshore Wind Turbine	-
P	Perimeter of each welded segments of each turbine tower	m
PLA	Product Line Analysis	-
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses	-
PM	Preventative Maintenance	-
ReCiPe	Resource Use, Emissions, and Health Impacts	-
REPA	Resource And Environmental Profile Analysis	-
RNA	Rotor Nacelle Assembly	-
t_F	Total downtime due to failures	h

Symbol or Abbreviation	**Description**	**Unit**
TP	Transition Piece	-
TLP	Tension Leg Platform	-
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts	-
USEtox	Unified System for the Evaluation of Toxicity	-
WMEP	Wind' monitoring program	-
WOW	Wait On Weather	-
WT	Wind Turbine	-
WTG	Wind Turbine Generator	-

1 Introduction

1.1 Background

Rapid urbanization and population expansion have raised the global need for energy, and the world's energy demand is expected to rise by 50% in the coming years [1]. Modernization in several industries leads to rapid increases in energy usage and depletion of fossil fuels which is the primary source of energy today. Moreover, burning fossil fuels to produce energy, negatively impacts the ecosystem such as the greenhouse effect [2]. It is also important to consider the economic aspect: for nations that are not gifted with their natural resources, the cost of producing electricity is several times higher due to purchasing of natural resources from countries that possess mineral resources [3].

To address climate change and energy security challenges resulting from fossil fuels, new power generation methods are introduced [2]. Renewable energy sources are considered a sustainable alternative for electricity generation, and these primarily include solar, wind, tidal, hydro, and biomass [2]. The international renewable energy agency (IRENA) predicts that by 2050, a 14 TW increase in worldwide renewable energy capacity which would require a five-fold growth of present capacity and emerging technologies will account for 45% of CO_2 emissions reductions [4].

One of the most available and environmentally friendly renewable energy sources to meet this prediction is wind power [2]. A decade ago, wind power was seen as a minor supplement to hydropower rather than a main source of energy, however, this perception is changing [5].On top of that, among offshore renewable energy sources, offshore wind energy appears to be the most promising for the upcoming years and decades due to higher and steadier wind speeds in open seas [6], [7]. The first offshore wind turbine, with a capacity of 220 kW and located 250 meters offshore beyond the beach, was installed in Sweden in 1990. This marked the beginning of offshore wind turbine technology. With 11 offshore wind turbines and a total capacity of 4.95 MW, Denmark established the first offshore wind farm in 1991. The majority of offshore wind turbines installed during this period were bottom-fixed, except Hywind Tampen in Norway, WindFloat Atlantic in Portugal, and Fukushima in Japan with floating substructures [7]. These floating offshore wind farms were developed to capture wind energy in deep waters, where traditional bottom-fixed solutions are not economically viable [8].

According to DNV’s global energy transition outlook [9] wind energy is expected to experience significant expansion and by 2050, wind energy is projected to increase ninefold, constituting 11% of the global primary energy mix.

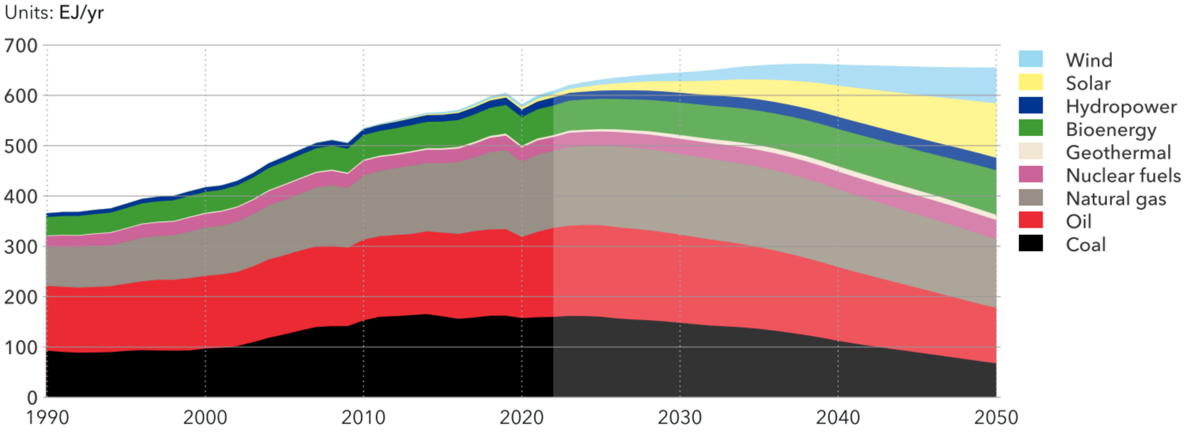

Figure 1.1 World primary energy supply by source from 1990 with a forecast to 2050 [9].

Nevertheless, despite generating clean electricity during operation, offshore wind turbines contribute to environmental impacts throughout their entire life cycle, including stages like manufacturing, installation, and decommissioning.[10]. Also, even though offshore wind energy has large net profits, the higher capital, installation, and maintenance expenses counterbalance the economic benefits [7]. Offshore wind technology's environmental impact and energy performance can be measured and the most commonly used assessment method is LCA [10].

1.2 Research Methodology

A brief overview of the research methodology is presented in this section. A three-level approach was adopted, as illustrated in Figure 1.2. In level 1 by applying a scoping literature review some previous studies were selected, reviewed and relevant content was extracted. The detailed review process is elaborated upon in Chapter 2.

In level 2 the LCA framework was constructed, including defining, the goals, scope of the LCA, boundaries, and functional unit (FU). Chapter 4 provides a comprehensive overview and background understanding of the LCA concept, while Chapter 5 delves into the methodology employed for conducting LCA in detail.

Additionally, level 2 consists of selecting two base case scenarios. The selected base case farms are Dogger Bank (phase C) bottom-fixed offshore wind farm (BFOW) and Hywind Tampen floating offshore wind farm (FOWF). The reason for selecting these two base cases was that they represent the utilization of the latest technologies and the largest turbine sizes in offshore wind energy. These base cases were chosen as benchmarks for comparisons, to identify the key factors influencing environmental impacts. General information about offshore wind turbine (OWT) technologies has been presented in Chapter 3. The next step in level 2 of this research was conducting life cycle inventory analysis (LCIA). During this step, data were gathered for each unit process being evaluated, including energy inputs, raw materials, and emissions. Chapter 6 has been allocated to LCI and basic calculations. The finalized data was given to the openLCA® software. This process utilized the ecoinvent database along with Recipe 2016 v1.03 midpoint (H) methodology.

The LCIA results were analyzed, the sensitivity of the results to some parameters was examined Furthermore, the results were compared with existing literature by applying a harmonization method. Finally, the interpretation of the results was conducted. Chapters 7 and 8 are dedicated to presenting the findings, discussion, and conclusions. Finally, some recommendations for further research are provided.

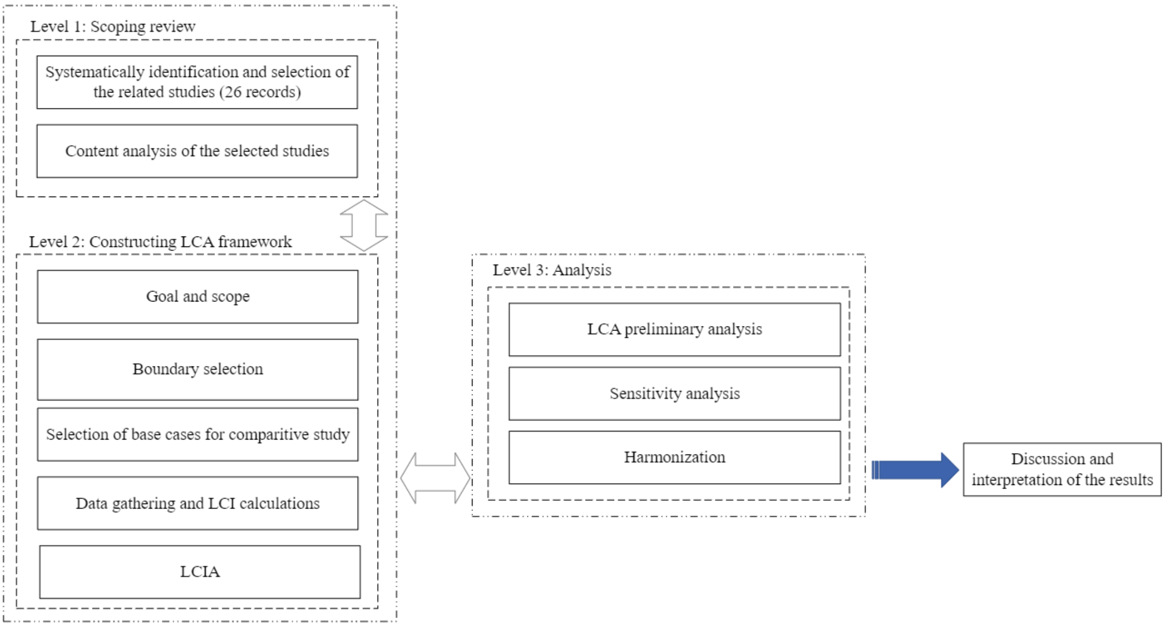

Figure 1.2 An overview of research methodology levels, inspired from [11]

2 Literature review

Building research on existing knowledge is crucial in all academic disciplines. It is critical for academics to accurately linking their work to existing knowledge. However, this endeavor has become increasingly difficult, where knowledge generation is rapid but scattered and interdisciplinary. This complexity makes it difficult to keep up with the latest research and evaluate collective data in specific areas. As a result, the literature review emerges as an important research tool, requiring the systematic collection and synthesis of prior research. For a literature review to be deemed a credible research methodology, it must follow specific procedures to ensure accuracy, precision, and reliability [12]. To achieve these criteria, this study investigated an appropriate literature review methodology, which will be elaborated upon in the following sections.

2.1 Finding a Proper Literature Review Method

To decide on the review method, a Google search was performed to explore different literature review methods. Initially, 20 websites and articles were reviewed, each discussing various methods. In total, 26 literature review methods were identified. These methods were then organized into a table with their sources for reference. Finally, the first four methods which were repeated most in all 20 references were chosen for further study. The results are presented in Table 2.1 and list of used sources are presented in Appendix B. The source column shows the websites that referred to the corresponding literature review method. The four methods with most repetition was chosen for the next step.

Table 2.1 List of literature review methods.

No.	Method Name	Source[1]
1	Narrative or traditional literature reviews	(1),(2),(3),(4),(5),(6), (7), (8),(10), (11),(12), (15), (18)
2	Critically Appraised Topic (CAT) or Critical Review	(1),(3), (4), (11), (18)
3	Scoping reviews	(1),(2),(4),(5),(6),(7), (8),(9), (11), (12), (13), (14), (15), (18), (19)
4	Systematic literature reviews	(1), (2), (4), (5), (6), (7), (8), (9), (11), (12), (13), (14), (15), (18), (19)

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[1] The list of these sources is provided separately in Appendix B

5	Annotated bibliographies	(1)
6	Argumentative literature review	(2), (8), (13), (14), (15),(17)
7	Integrative literature review	(2), (4), (9), (11), (13), (14), (15), (17), (18)
8	Theoretical literature review	(2), (4), (8), (13), (14), (15), (16)
9	Descriptive or Mapping Reviews	(3), (11)
10	Forms of Aggregative Reviews	(3)
11	Realist Reviews	(3), (18)
12	Meta Analysis	(4),(6), (7), (8),(10), (12), (18), (19)
13	Methodological Review	(4), (8), (13), (14), (16), (17)
14	Cross-Disciplinary Review	(4)
15	Descriptive Review	(4)
16	Rapid Review	(4),(10), (12), (18), (20)
17	Conceptual Review	(4), (6), (18)
18	Library Research	(4)
19	State-of-the-Art Review	(6), (18)
20	Meta-synthesis	(7)
21	Chronological	(8), (13), (14), (16), (17), (18)
22	By trend	(8)
23	Thematic	(8), (16), (18)
24	Semi-Systematic Review	(9)
25	Mixed methods/mixed studies	(10), (12), (18), (19)
26	Umbrella Literature Review	(10), (12), (18), (19)

Based on the results, the four most common methods were found and have been listed in Table 2.2.

Table 2.2 The four most common literature review methods.

No.	Method
1	Systematic literature review
2	Narrative or traditional literature review
3	Scoping review
4	Integrative literature review

The next step was performing research on these four methods to determine which one best aligned with the goals and scope of this study.

Systematic literature review: Systematic literature reviews aim to answer specific research questions by thoroughly evaluating relevant literature, which frequently involves numerous authors following defined protocols to ensure transparency. They originated in medical science and have since expanded to include evidence-based investigations in a wide range of areas. Systematic reviews differ from standard literature reviews in that they are more focused and include components such as eligibility criteria, search methodologies, validity assessment, and results interpretation. Regardless of the effort invested, this meticulous method offers essential insights for both practitioners and scholars [13].

Narrative or traditional literature review: These reviews provide a general overview of a research topic without employing a specific method. They collect and interpret data without a clear procedure, frequently offering personal opinions on findings. Even if professionals are involved, they may be biased due to their own ideas. These reviews may be useful for broad topics, specific scholars, or time constraints [14].

Scoping review: Scoping reviews thoroughly explore broad research topics by meticulously evaluating the literature to determine its scope and coverage within a specific area. While scoping reviews are appropriate for broad topics, systematic reviews are used to address particular research questions. Additionally, despite systematic reviews, scoping reviews do not include a quality assessment of evidence [15].

Integrative Literature Review: This type of review goes beyond analyzing primary research findings, providing new insights and summarized knowledge on a topic. Unlike a formal systematic review, an integrative literature review includes not only primary research studies but also other documents like opinions and policy papers [16].

2.2 Research Design

In the present study the scoping review was implemented to analyze and review available literature trends, limitations, and gaps. In essence, a scoping review aims to swiftly summarize the underlying principles underpinning a study subject, as well as identify the key sources and types of data available. Such reviews can be undertaken independently, especially when a topic is complex or has not been extensively studied previously [17]. This method is not a mapping review nor a systematic review because it does not intend to critically assess the identified literature [18].

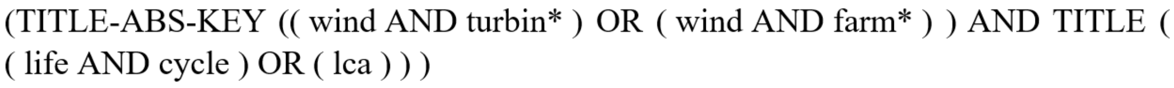
Four common reasons why a scoping literature review is taken can be listed as below [19], [20]:

1- To provide an overview of research activity by analysing its scope, range, and nature, particularly in complex subjects where accessible material may not be obvious.
2- To assist in determining whether a complete systematic review is feasible by examining existing literature.
3- To summarize and distribute research findings, making them available to policymakers, practitioners, and consumers who may not have the means to conduct independent research.
4- To identify gaps in the literature, including regions where no study has been undertaken, but not evaluating the quality of the research.

2.2.1 Procedure

The process of literature review under scoping method consists of below steps, using the same method used by [18],[20]:

1- The Scopus database was used as the scientific database, with the keywords in the title of this study and modify them in a way that broaden the search results, for instance, adding asterisks (*) at the end of a word in the search box helps indicating words with identical first letters. In this way, farm* can find both farm and forms. The search string used in Scopus database is indicted in Figure 2.1. This was first used to search within title, abstract and keyword.



(TITLE-ABS-KEY ((wind AND turbin*) OR (wind AND farm*)) AND TITLE ((life AND cycle) OR (lca)))

Figure 2.1 The search string used in Scopus database.

2- In the first step,1975 articles were obtained, as this number was too high, the search limited to tittle only, and as a result the number of articles dropped to 171.

3- As in recent years there have been so much interest among scholars in LCA of wind farms, a new filter was introduced to search for literature in years between 2020 and 2024, the number of materials reduced to 61.

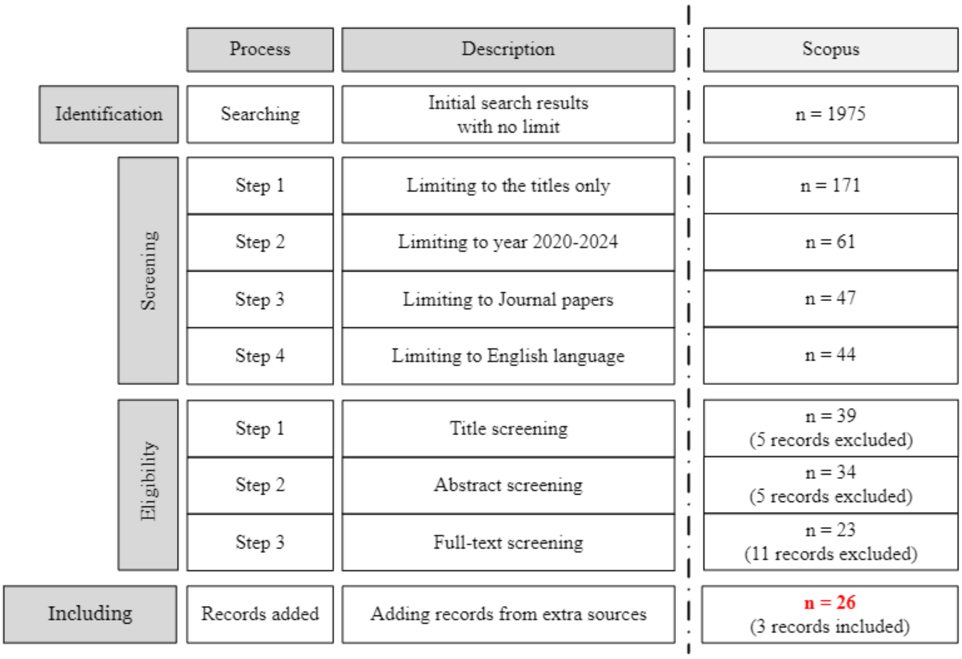
4- In this study the focus of literature review was put based on only articles, by adding this filter, 14 more documents dropped, and the number of results became 47.

5- In the next step, the language was limited to only English, so 3 more dropped and there were 44 articles ready to start reviewing.

6- The studies' eligibility was examined in three stages: title, abstract and full-text screening. During each step, five, five, and 11 articles, respectively, were determined to be irrelevant and were removed from the list. Overall, the list in this step comprised of 23 publications.

7- Three relevant master theses were found separately and added to the list, the final number of documents became 26 records.

The procedure is shown by using a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram in Figure 2.2.



	Process	Description	Scopus
Identification	Searching	Initial search results with no limit	n = 1975
Screening	Step 1	Limiting to the titles only	n = 171
	Step 2	Limiting to year 2020-2024	n = 61
	Step 3	Limiting to Journal papers	n = 47
	Step 4	Limiting to English language	n = 44
Eligibility	Step 1	Title screening	n = 39 (5 records excluded)
	Step 2	Abstract screening	n = 34 (5 records excluded)
	Step 3	Full-text screening	n = 23 (11 records excluded)
Including	Records added	Adding records from extra sources	**n = 26** (3 records included)

Figure 2.2 PRISMA flow diagram, inspired from [20].

2.3 Literature Review Summary

The 26 final records were carefully reviewed, and useful data were extracted. The overview of this review is presented in two separate tables; Table 2.3 provides a general overview of the wind farms technology data, and Table 2.4 presents a general overview of the LCA methodology data found in literature. The comparison of the amount of emissions in literature with the results of current study is provided separately in the Chapter 7. Among reviewed studies, only one study was found that compared floating and bottom fixed (study [1]) and this thesis only considered decommissioning stage. There was one study that conducted LCA on both offshore and onshore wind farms simultaneously (study [10]). Five studies conducted LCA on a single WT, one study performed LCA of both wind turbine (WT) and wind farm (WF) and the rest of studies performed LCA of WFs. Most studies assumed a lifetime of 20 years. Most studies applied a cradle-to-grave approach, SimaPro®, ecoinvent and Recipe were the most commonly utilized software, database and LCIA method respectively.

Table 2.3 A general overview of the wind farms technology data found in literature.

Country/Region	Capacity (MW)	Type	Farm/Turbine	Lifetime (Years)	Ref
China	40	Onshore	Farm	Six scenarios	[21]
Thailand	10	Onshore	Turbine	-	[22]
Colombia	19.5	Onshore	Farm	20	[23]
Scotland	6 and 9.5	Offshore (Floating)	Farm	25	[8]
France	24	Offshore (Floating)	Farm	20	[24]
-	2	Onshore	Turbine	20	[25]
Malaysia	105	Offshore (Floating)	Farm	19	[7]
France	-	Onshore		25	[26]
-	2	Offshore (Floating)	Turbine	20	[27]
-	Various	Both	Both	20 for Offshore	[10]
India	56.1	Onshore	Farm	-	[10]
China	Various	Offshore	Farm	-	[28]
Ethiopia	Various	Onshore	Farm	20	[29]
-	Various	Onshore	Farm	-	[30]
China	Various	Onshore	Farm	-	[31]

Libya	20	Onshore	Farm	20	[32]
Italy	2793	Offshore (Floating)	Farm	30	[33]
-	Various	Onshore	Turbine	-	[34]
-	Various	Onshore	Turbine	20	[35]
Scotland	15	Offshore (Floating)	Farm	20	[36]
UK	Various	Offshore (Floating)	Farm	20	[37]
-	Various	Offshore (Floating)	Farm	25 to 30	[38]
Turkey	45.7	Onshore	Farm	Six scenarios	[39]
USA	600	Offshore (Floating)	Farm	25	[40][2]
Greece	2	Offshore (Floating)	Farm	20	[41][2]
UK	Various	Offshore (Both)	Farm	25	[1][2]

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[2] These three studies were master theses, as mentioned in PRISMA flow diagram; they were found separately and added to the records.

Table 2.4 A general overview of the LCA methodology data found in literature.

LCA Approach	LCA software	Database	LCIA Methodology	Ref
-	GaBi	Survey data-GaBi	-	[21]
cradle to grave	SimaPro	Ecoinvent Database	ReCiPe	[22]
-	-	-	ILCD with 10 impacts	[23]
cradle to grave	SimaPro 9.1	Ecoinvent v3.6	ReCiPe	[8]
cradle to grave	-	Ecoinvent v3.3	ReCiPe	[24]
cradle to grave	-	-	-	[26]
cradle to cradle	Gemis 5	Europa Database	-	[27]
-	-	Ecoinvent	ReCiPe Midpoint 2016 (H)	[10]
cradle to grave	SimaPro7	Ecoinvent	CML 2001	[10]
cradle to grave	-	-	CML-IA	[28]
cradle to grave	SimaPro 8.0.3.14	Ecoinvent	CML, IMPACT 2002	[29]
cradle to grave	SimaPro 9.3	Ecoinvent 3.7.1	EPD (version 2018)	[33]
cradle to cradle	Gemis	-	-	[34]
-	OpenLCA® and Gemis	-	ReCiPe	[35]
-	SimaPro	modified ecoinvent	ReCiPe 2016 v1.1	[36]
cradle to grave	GaBi 7.3	Survey data-GaBi	CML 2001	[39]
cradle to cradle	SimaPro	Ecoinvent	Only GWP was calculated	[40][3]
cradle to cradle	Microsoft Excel®	Ecoinvent	Only GWP was calculated	[41] [3]
-	SimaPro	Ecoinvent	ReCiPe	[1][3]

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[3] These three studies were master theses, as mentioned in PRISMA flow diagram; they were found separately and added to the records.

3 Offshore Wind Technologies

3.1 History of Harnessing Wind Energy

Wind power has been utilized by humans since ancient civilizations. Wind was used to drive ships in Mesopotamia as early as the fifth millennium BCE, according to historical records. From the seventh to ninth centuries AD, Persia used vertical axis windmills for practical purposes such as flour milling and water pumping. Horizontal axis windmills first appeared in northern Europe in the 12th century and were used for grain milling [42].

In the early 1880s, the idea of utilizing wind power to generate electricity evolved. Professor James Blyth of Anderson's College in Scotland is largely credited with creating the first wind-powered electrical generator in July 1887. Blyth used this method to power his vacation cottage in Marykirk, Scotland, making it the world's first home to receive electricity from wind energy. Poul la Cour, a Danish inventor, greatly improved wind turbine technology in 1895, motivated by scientific innovation as well as a social goal. Raised on a farm, la Cour hoped to employ wind turbines to revive rural communities facing depopulation due to industrialization. By the early twentieth century, land-based wind turbines were widely used in Denmark, powering rural sites such as homes, schools, farms, and villages. By 1908, the country had erected 72 wind turbine generators, indicating a significant move toward decentralized power generation through wind energy [42]. During the 1930s and 1940s, Denmark, Germany, Russia, France, and the USA planned and built larger wind turbines ranging from 100 kW to 1 MW [43].

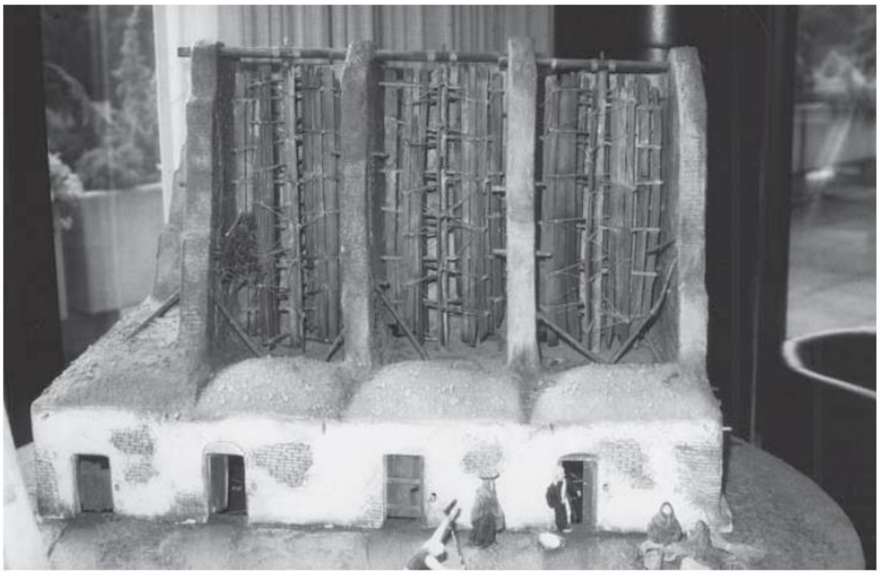


Figure 3.1 A model of an ancient windmill located in the Sistan region of Iran [44].

3.1.1 Large Onshore Wind Farms Development

Since the 1980s, the use of wind turbines in large wind farms has been a trademark of modern power generation, attempting to make use of the huge geographical breadth of wind resources. In California, wind farms built in the 1970s and 1980s contained multiple relatively tiny wind turbines, each generating less than 100 kW, grouped in arrays of more than 100 turbines. One advantage of a large wind farm is the substantial amount of electricity it produces, which justifies the costs connected with grid connection. Furthermore, maintaining a large wind farm provides significant advantages, as resources such as workers, tools, parts, and facilities can be centralized or situated near the site, easing maintenance activities [43].

3.1.2 Emergence of Offshore Wind

For years, European scientists and engineers have realized that offshore wind turbines could generate more energy than onshore turbines due to greater and unhindered wind resources, as well as less man-made and topographical barriers. The inspiration for offshore wind in Europe arose from the continuously higher and unobstructed winds encountered at sea, which frequently exceeded 8 m/s, well above the 3-5 m/s range found on land. Offshore wind farms also addressed land-use and visual impact concerns that are common with onshore installations. However, the first growth of offshore wind farms in Europe was primarily motivated by commercial responses to the shortage of suitable onshore locations and conflicts in land-use issues [42].

In 1991, the first offshore wind farm was built in Vindeby, Denmark, with 11 turbines located in non-tidal Baltic waters near Fyn Island. Following Vindeby, numerous further small-scale offshore wind projects were implemented in Denmark, the United Kingdom, and the Netherlands in a decade. Each of these projects located within a distance of less than 7 kilometers from the shore and in sea depths of less than 8 meters [42]. Due to the high capital expenditure necessary for offshore installation, developers have increased the size of wind farms to lower overall expenses [42]. In 2000, Denmark's Middelgrunden wind farm, consisting of 20 Bonus B76 turbines with a diameter of 76 m, became the first major offshore wind farm [43].

Offshore wind farms initially faced higher costs and reliability issues than onshore projects, which hindered industry support. Despite isolated commercial projects in northern Europe in the 1990s, most experts in the United Kingdom predicted offshore wind would be financially unviable until about 2020. However, by the early 2000s, events including as the EU's approval of the Kyoto Protocol, energy security concerns, and economic crises had transformed public opinions, paving the way for growing political and societal support for offshore wind in Europe [42].

3.2 Components of Wind Turbine

Most wind turbines have a conventional design, which typically consists of a three-bladed turbine coupled to a horizontally mounted generator. Figure 3.2 and Figure 3.3 show the common components of a wind turbine, such as the rotor-nacelle assembly (RNA) and tower. The fundamental idea is to convert the kinetic energy of the wind into rotating kinetic energy within the turbine, which is subsequently converted into electrical energy via a generator [45].

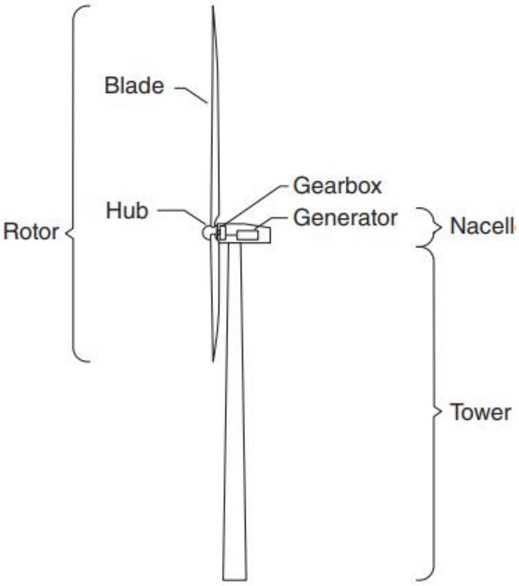


Figure 3.2 RNA (rotor-nacelle assembly) and the tower [45].

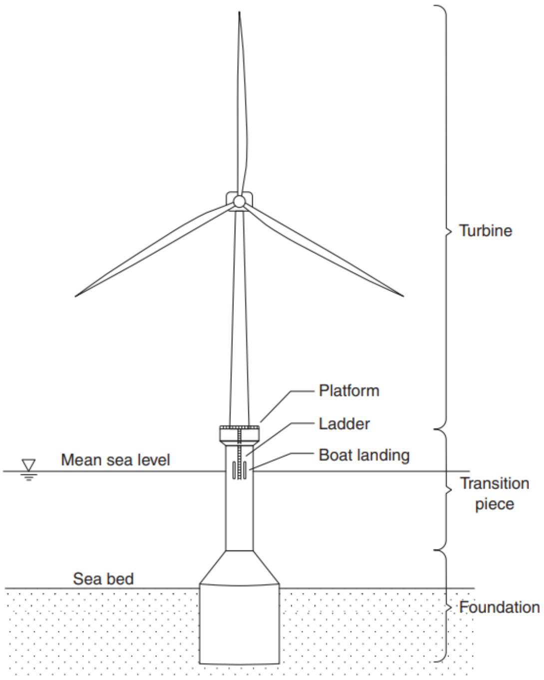


Figure 3.3 The key parts of a wind turbine [45].

The nacelle, on top of the tower (Figure 3.4), varies in design and size depending on the wind turbine. Within the nacelle, a generator converts the wind turbine's rotation into power. A gearbox, usually with a speed ratio of 1:100, is used to boost the speed of the low-speed shaft, which drives the generator at high speeds. The low-speed shaft runs from the nacelle to connect to the rotor hub, which houses the turbine blades. These blades rotate at a slow speed, usually about 20 RPM [45].

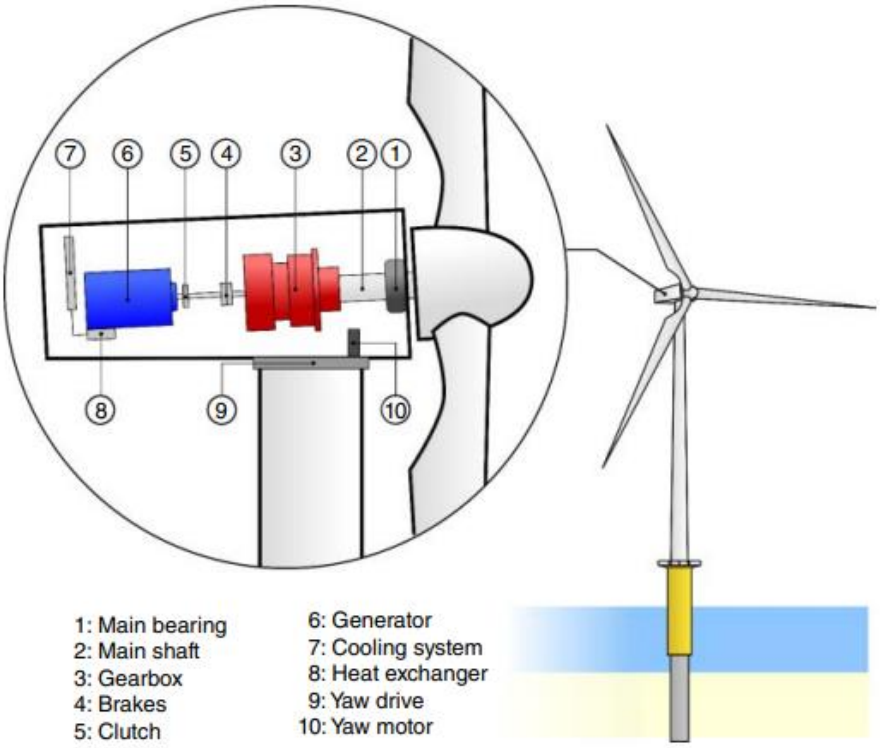


Figure 3.4 A wind turbine schematic [45].

Since offshore lifting operations are relatively costly, lightweight generators become critical. These lightweight designs can be hoisted by smaller, more affordable vessels. Furthermore, because offshore maintenance is expensive, designs that are both low-maintenance and durable are favored. This is where direct-drive systems excel. They reduce the need for gearboxes (and other complex components) and feature fewer moving parts, making maintenance easier and requiring fewer replacement parts [46]. Figure 3.5 shows different components of a direct-drive wind turbine.

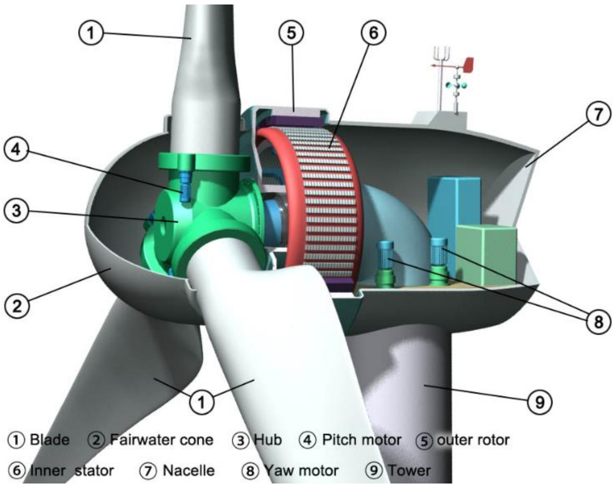


Figure 3.5 Different components of a direct-drive wind turbine [47].

It is worth noting that hybrid wind turbines also exist which is a combination of two systems equipped with a gearbox that has a restricted number of steps [45].

3.3 Foundation Types

The design of foundations is a vital aspect that frequently determines the economic feasibility of a project. When selecting and designing a foundation for a specific site, a variety of considerations must be considered. These factors include ease of installation in various weather conditions, diverse seabed conditions, installation logistics such as required vessels and equipment, and local environmental requirements, particularly noise.

There are two types of substructures:

1- A grounded system or bottom fixed structure which refers to a setup where the structure is firmly anchored to the seabed.
2- A floating system which involves allowing the structure to float while securing it to the seabed through a mooring system.

Figure 3.6 shows a diagram of wind turbines supported by a large-diameter column deeply sunk into the earth, known as a monopile. This sort of foundation is commonly used in the offshore wind sector due to its simplicity [45].

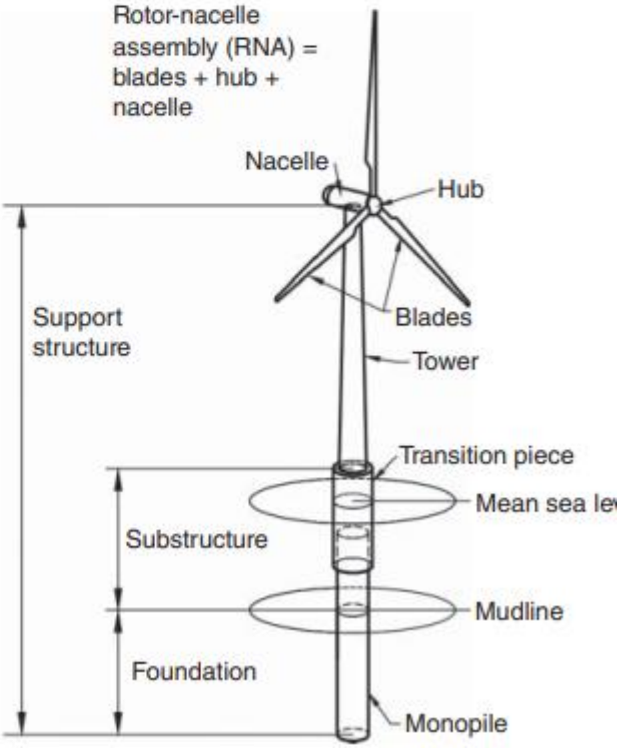


Figure 3.6 Monopile Foundation [45].

Figure 3.6 depicts various foundation types typically used today, adapted to different water depths. Suction caissons (Figure 3.7a) gravity-based (Figure 3. 7b), monopiles (Figure 3. 7c), foundations, are now used or being considered for depths of roughly 30 meters. Jackets or seabed frame structures supported by piles or caissons are now in operation or being planned for depths ranging from 30 to 60 meters. A floating system is being used for deeper waters, often greater than 60 meters (Tension leg platform and spar buoy floating as shown in Figure 3.7). However, factors other than water depth influence foundation selection, including seabed characteristics, site conditions, turbine specs, loading concerns, and economic viability [45].

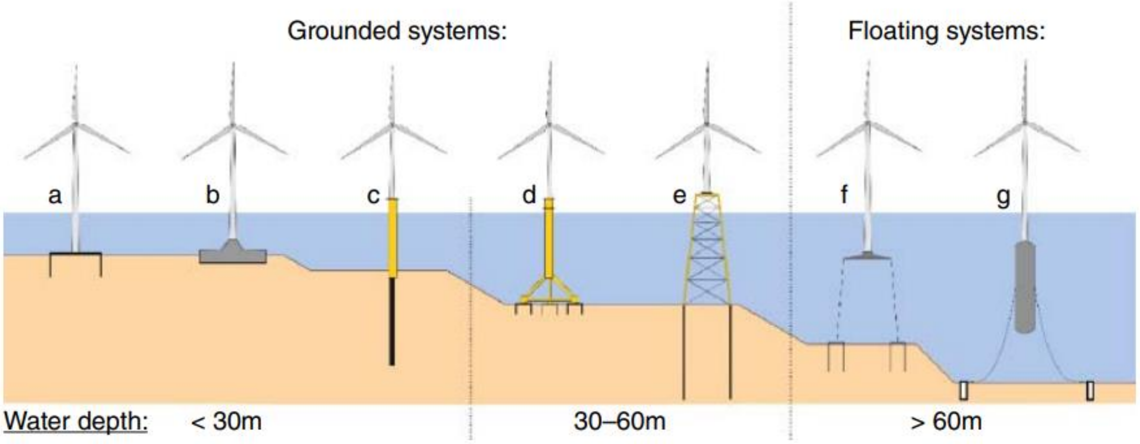


Figure 3.7 Various offshore wind turbine foundation types [48].

3.3.1 Pile Foundations

The most common foundation type for offshore wind turbines is a single large-diameter steel tubular pile, commonly known as a monopile. This foundation, illustrated in Figure 3.8, is made up of a massive steel pile that is typically 3 to 7 meters in diameter and is driven into the seabed to a depth of 25 to 40 meters. A steel tube, known as the transition piece (TP), links to the steel pile and acts as a platform for mounting the tower. The TP also accommodates boat landings and ladders for turbine access. Currently, this foundation design is extensively used for water depths of 25 to 30 meters [48].

The TP, is typically tubular in shape and has a slightly greater diameter than monopile, allowing it to be put atop the monopile. A flange on top of the transition piece connects it to the tower via nuts and bolts. This component weights roughly 200 tons and is around 25 meters tall [49].

These foundations are frequently hammered into the seabed with a steam or hydraulically powered hammer, a procedure that has become highly standardized due to the offshore oil and gas sector. Handling and installing enormous foundations require specialized vessels, such as floating or jack up vessels, equipped with large cranes, hammers, and drilling equipment. Pile driving causes noise and vibrations, hence the turbine components (Nacelle and Rotor) are normally installed after the piling process is completed [48] .

Figure 3.8 Large diameter monopile offshore wind turbines [45].

3.3.2 Gravity-based Foundations

The gravity foundation is designed to prevent uplift and overturning, so there is no tension between the support structure and the seafloor. This is accomplished by adding enough dead weight to stabilize the structure against overturning pressures. If the combined dead loads of the support structure and top (such as the tower and RNA) are insufficient, further ballast is required. Ballast materials may include rock, iron ore, or concrete. Installing these foundations frequently entails preparing the bottom to prevent tilting. Gravity-based constructions are often constructed from in-situ concrete or precast concrete modules [48].

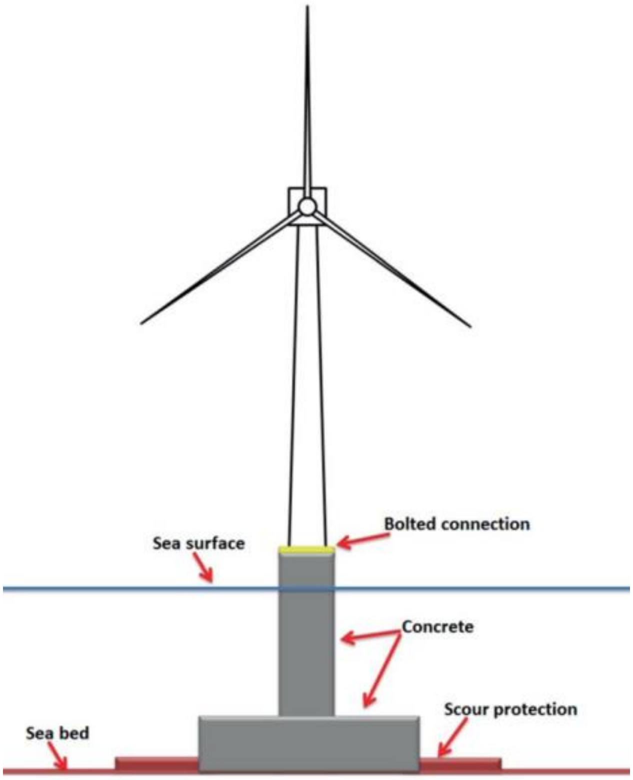


Figure 3.9 Schematic layout of a gravity-based offshore wind turbine [49].

3.3.3 Suction Buckets Foundations

Suction buckets, also known as suction caissons, resemble gravity-based foundations but have longer skirts around the outside. They effectively integrate design aspects from both the shallow and pile foundation types. A caisson is made of a solid circular cover and a narrow tubular skirt that extends below to a finite length, much like a bucket. Figure 3.10 shows a diagram of a suction caisson with associated language. Suction caissons are a relatively new concept in the offshore business. Caissons were first used roughly three decades ago as foundational structures for offshore oil and gas production platforms [48].

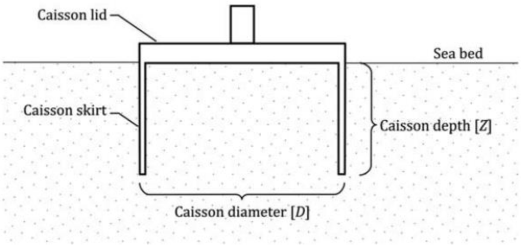


Figure 3.10 Suction bucket foundation layout [48].

3.3.4 Jacket Supported on Pile or Caissons Foundations.

A seabed frame or jacket supported by piles or caissons is commonly used as a supporting structure. These can be classified as Multipods, as shown in Fig. 10.15. Multipods have several points of contact between the foundation and the soil [48].

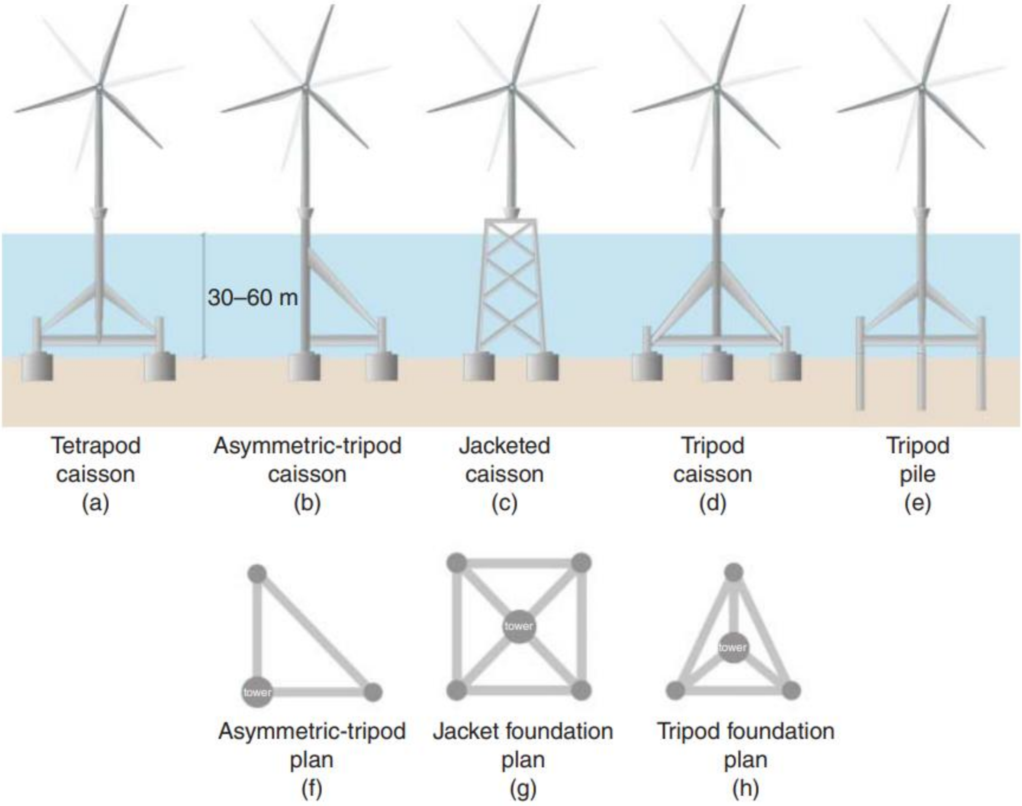


Figure 3.11 Multipod foundations [45]

3.3.5 Floating Foundations

While floating support structures are now less common in offshore wind projects, their use is going to increase as the industry seeks locations with deeper sea depths. As water depths increase, the costs of bottom-fixed turbines rise dramatically. There is continuing debate and research globally to establish the transition depth at which floating platforms become economically viable when compared to bottom-fixed turbines. This transition depth is normally in range of 50 to 100 meters. Factors such as the type of floater and site conditions might influence this transition depth. However, it is widely assumed that for water depths more than 100 meters, floating concepts will be the most cost-effective solutions. A comparison of rated power and water depth for floating and bottom fixed wind turbines is shown in Figure 3.12 [49].

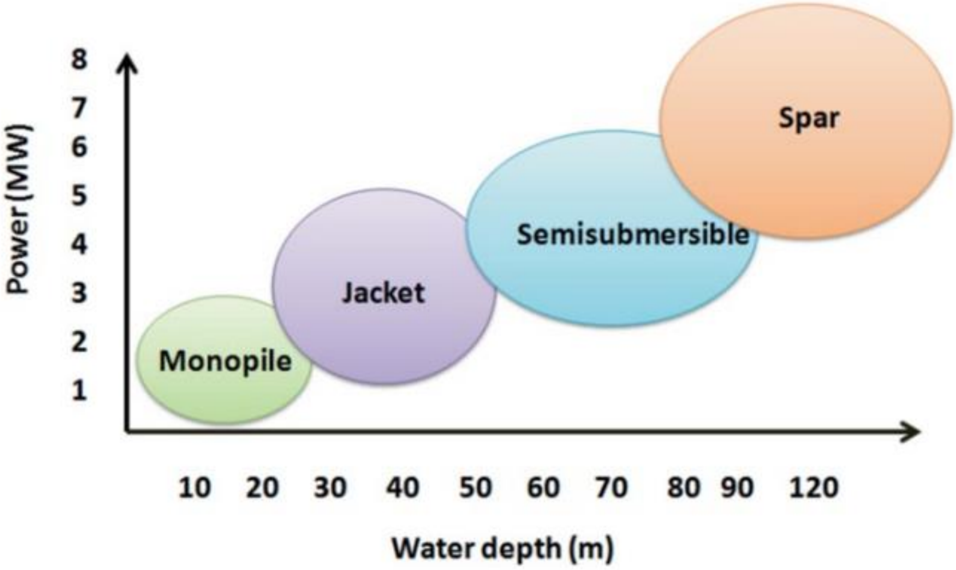


Figure 3.12 A comparison of rated power and water depth for floating and bottom fixed wind turbines [49].

The floating system can be divided into three principal categories as shown in Figure 3.13 [48]:

1- TLP (Tension Leg Platform) with mooring stabilization: This system uses tensioned mooring for stability and is securely fastened to the seabed to preserve buoyancy and stability.
2- Spar buoy with ballast stabilization, with or without the motion control stabilizer: This type of system has a deep cylindrical base for ballast, with the lower section being significantly heavier than the higher section. This arrangement positions the center of buoyancy higher than the center of gravity. While these constructions are simple and affordable in initial cost, they require larger water depths and are unsuitable in shallow environments. Motion stabilizers can be used to reduce the overall tilt of the system.
3- Semisubmersible buoyancy stabilization: This design combines ballasting and tensioning principles and requires a substantial amount of steel, as illustrated in Fig. 10.17B.

There are two types of anchors used to moor a floating system: surface and embedded anchors. One type of surface anchor is a huge, heavy container packed with rocks or iron ore. The efficiency of such anchors is dependent on both the anchor's weight and the friction between its base and the seabed. In contrast, embedded anchors include structures such as anchor piles which are crucial to floating wind turbine designs, suitable for deeper waters. Figure 3.14 depicts the Hywind concept (spar) [48].

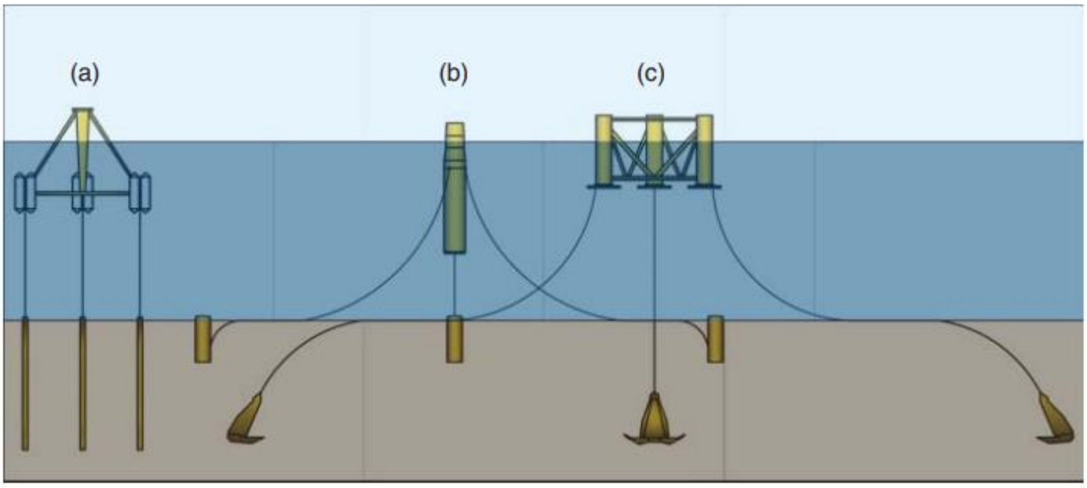


Figure 3.13 Main Types of floating wind turbine [45].

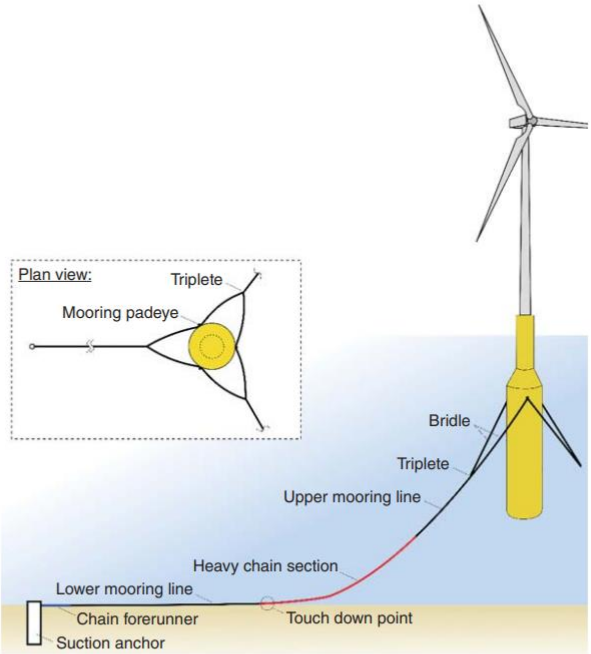


Figure 3.14 Spar buoy foundation used in Hywind project [45].

3.4 Wind Farm General Arrangement

Figure 3.15 depicts the components of a conventional wind farm. The wind farm's turbines are linked together via inter-array cables, forming an electrical collecting system that connects to the offshore substation. Additionally, export cables connect the offshore substation to the onshore grid connection [45].

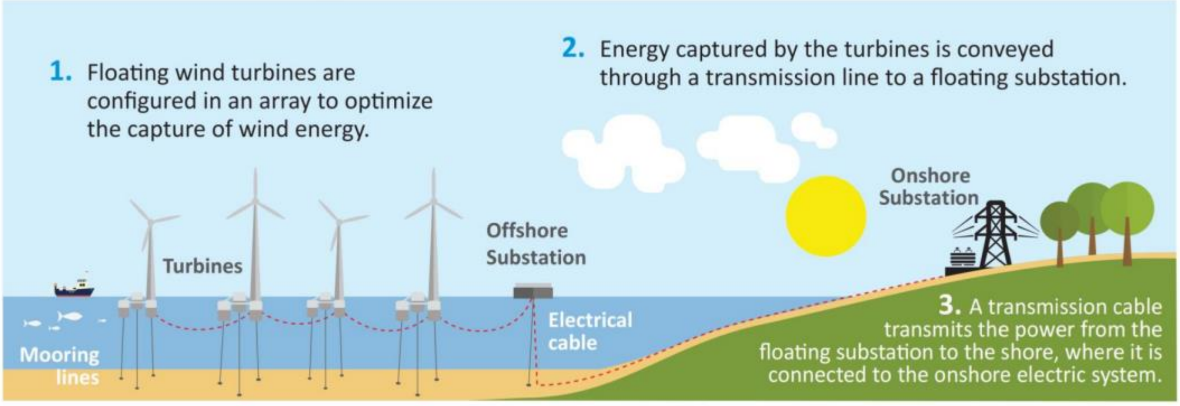


Figure 3.15 An offshore wind farm general arrangement [40].

3.4.1 Wind Farm Layout

Wind turbines in a wind farm are strategically positioned to maximize energy generation while minimizing capital expenditure (CAPEX), or upfront costs. The length of inter-array cables increases as the turbines are positioned more apart. As a result, turbine spacing provides an optimization challenge: striking a compromise between the wind farm's compactness (lowering CAPEX by reducing subsea cable costs) and providing enough separation between turbines to reduce energy loss caused by wind shadowing from turbines upstream [45].

Figure 3.16 Wake turbulence in an offshore wind farm [45].

3.5 Substation and Power Systems

3.5.1 Substations

Substations act as the essential links between electricity generation, transmission, and distribution networks. In the case of offshore wind energy, the power generated by individual turbines is sent to the offshore substation. The turbines are connected to this substation via cables rated between 33 and 66 kV. The substation's principal duty is to contain the high-voltage (HV) and medium-voltage (MV) electrical components required for transmission turbine-generated power. Export cables then transfer this power from the substation to the shore, where it is integrated into the electrical system via another onshore substation [50]. Figure 3.17 illustrates an example of a high voltage alternating current (HVAC) wind farm [50].

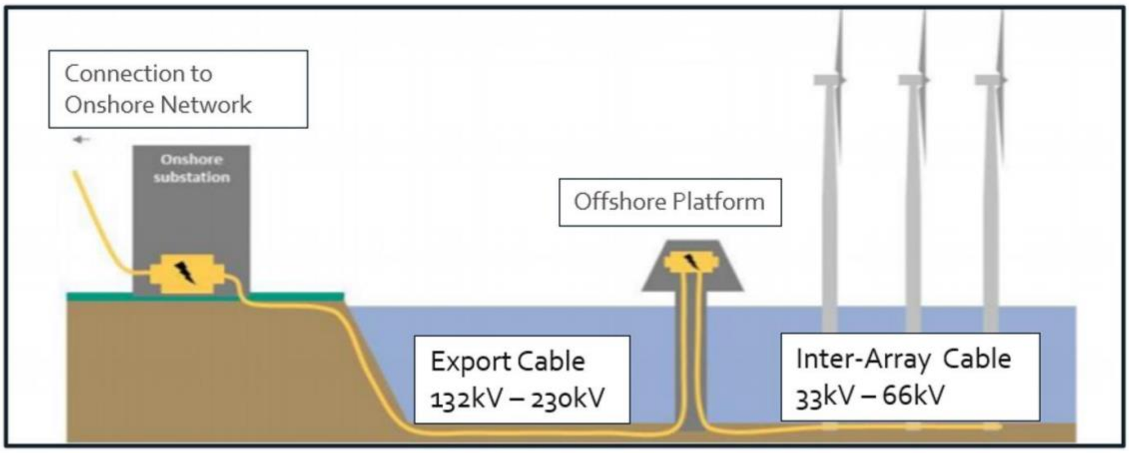


Figure 3.17 an example of a high-voltage alternating current (HVAC) wind farm [50].

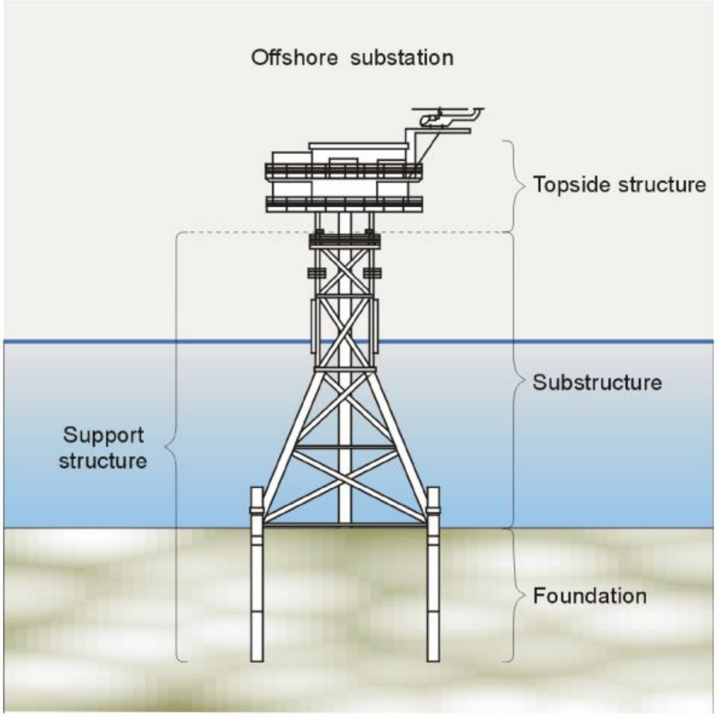


Figure 3.18 Typical offshore substation structure [51].

3.5.2 Power Systems

Offshore wind energy systems utilize two types of cables: array cables and export cables. Array cables transmit electricity from multiple wind turbines to an offshore substation. Typically operating at 66 kV, these array cables are expected to be upgraded to 132 kV in the future for better efficiency. Export cables, on the other hand, have higher capabilities and are often rated at 220 kV. They transfer power from the offshore substation to the onshore substation for further grid integration. The rating of export cables in next wind farms could increase to 275 kV. In some cases, particularly for smaller wind farms, an offshore substation may be unnecessary, and the array cables can be connected directly to the onshore substation [52].

Floating wind turbines will utilize dynamic array cables, in the area closest to the wind turbine, while bottom fixed wind turbines will use static cables. Dynamic cables are more durable and flexible than static cables, allowing them to withstand the stresses and motions experienced during the operation of floating turbines. The decision to utilize a combination of static and dynamic cables, including joints, is based on availability and a cost-benefit analysis of cable procurement and installation [52]. Figure 3.19 shows cable accessories of a dynamic array cable:

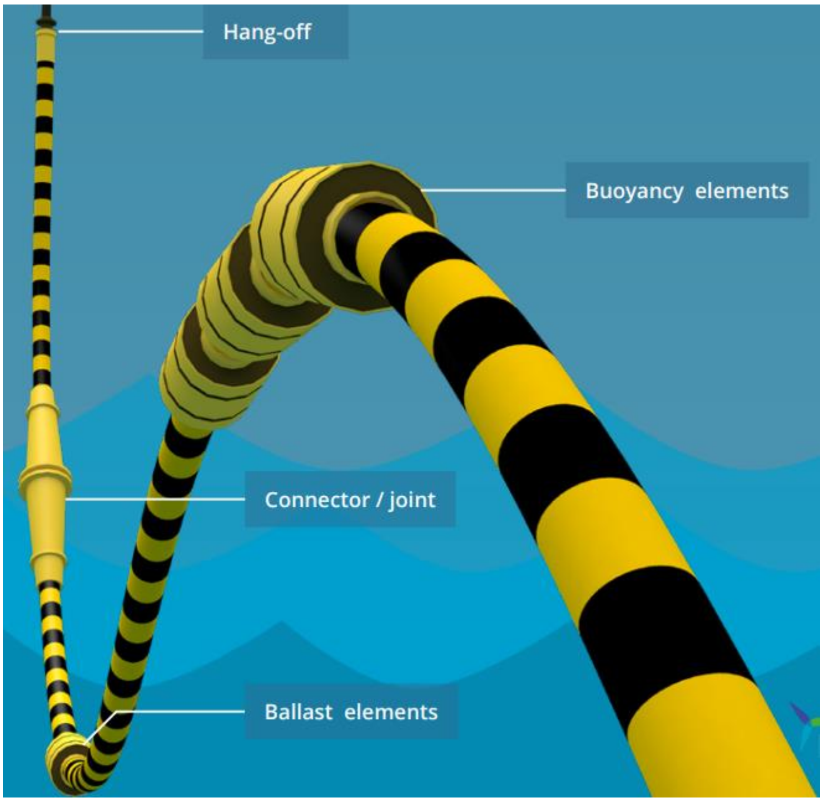


Figure 3.19 Cable accessories of a dynamic array cable [52].

Figure 3.20 shows application of dynamic, static and export cables.

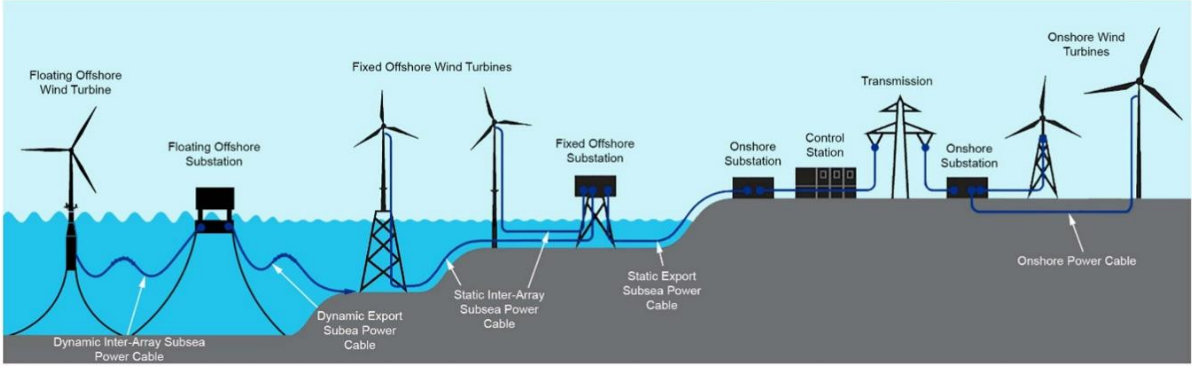


Figure 3.20 Application of dynamic, static and export cables [53].

3.5.2.1 Composition of a submarine cable

A submarine cable comprises mostly of a conductor, insulation, and outer shielding. The conductor can be aluminum or copper, while the insulation varies according on the cable type and intended use. Typically, the exterior shielding is constructed of polypropylene [54].The detailed description of submarine cables is given in Table 3.1 and Figure 3.21 shows a three core cable [32].

Table 3.1 Description of array and export cables [52].

Cable type	Sub-components	Typical weights	Typical dimensions
Static array cables	Aluminium core, insulation material – commonly cross-linked polyethylene (XLPE) or ethylene propylene rubber (EPR), armouring material (steel or lead wire), polypropylene binding ropes	Approximately 60 kg/m or more (for a typical 66kV cable)	120mm OD to 200mm OD. Length is project dependent, typically 1.5 km or more
Dynamic array cables	Copper core, insulation material – commonly XLPE or EPR, armouring material (steel or lead wire), polyethylene sheathing.	Approximately 70 kg/m or more (for a typical 66kV cable).	Typically, with an outer diameter (OD) of 140 mm or larger, are longer, often exceeding 1.5 km, and are project-specific
Export cables	Copper (or aluminium) core, insulation material – commonly XLPE or EPR, armouring material (steel wire), sealing material (lead) and polyethylene sheathing.	Approximately 70 kg/m -150 kg/m	200mm - 300 mm outer diameter

Figure 3.21 Components of a three core cable [54].

4 Life Cycle Assessment (LCA)

4.1 LCA Definition

The metaphor of the life cycle is taken from the study of biology. For instance, a butterfly's life cycle begins with an egg that bursts to release a caterpillar, which develops into a pupa, from which a butterfly emerges and ultimately perishes after laying eggs to resume the cycle. Like this, the life cycle of a man-made product begins with the collection and extraction of materials, then moves on to manufacturing, usage, and, at the end of the process disposal of the object as waste. Reuse and recycling can be thought of as "new eggs" in the life cycles of other manufactured goods. LCA focuses on examining physical items like products. When we say, "product system," it means we're looking at the entire lifecycle of the product, including all the steps needed to make it work. Life cycles are the sequential and connected phases of a product system, starting with the extraction of raw materials from natural resources and ending with their ultimate disposal [55],[56] . Even though LCA is mostly used to analyze product systems, it may also be used to analyze more intricate man-made items, such as infrastructure, cities, businesses' energy, transportation, and waste management systems[55].

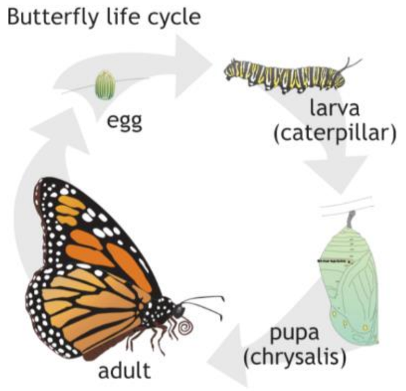


Figure 4.1 The life cycle of a butterfly [56].

Figure 4.2 The life cycle of a product [56].

The following definition of LCA can be found in the introduction section of the international standard ISO 14040 [57], which serves as a framework for conducting LCA:

“LCA studies the environmental aspects and potential impacts throughout a product’s life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.”

What sets LCA apart from similar methodologies such as product line analysis (PLA) is the absence of economic and social elements [58].

LCA approach is not as recent as many people think. There have already been reports of life cycle thinking approaches in earlier literature. Patrick Geddes, a Scottish economist, and biologist created a method that was similar to LCI as early as the 1880s. His area of interest was the supply of energy, particularly coal. The resource and environmental profile analysis (REPA) at Midwest Research Institute in the United States was where the first LCAs in the modern sense were carried out around 1970 [58]. Today, the most common approach for simulating and calculating the environmental effects of products and processes is LCA [18].

The life cycle assessment can be used in many different situations and can help with [59]:

- Identifying solutions to increase environmental the performance of products throughout their life cycle,
- Decision-makers in industry, government, or other organizations can be informed,

- Select applicable environmental performance indicators and measuring approaches, and
- Marketing

The product life cycle has five phases: extraction, production, distribution, usage, and end-of-life. The assessment approach is commonly used from cradle to grave, but it can also be employed from cradle to gate, gate-to-gate, cradle-to-customer, or gate-to-grave, or cradle-to-cradle.

Figure 4.3 demonstrates the various perspectives [59].

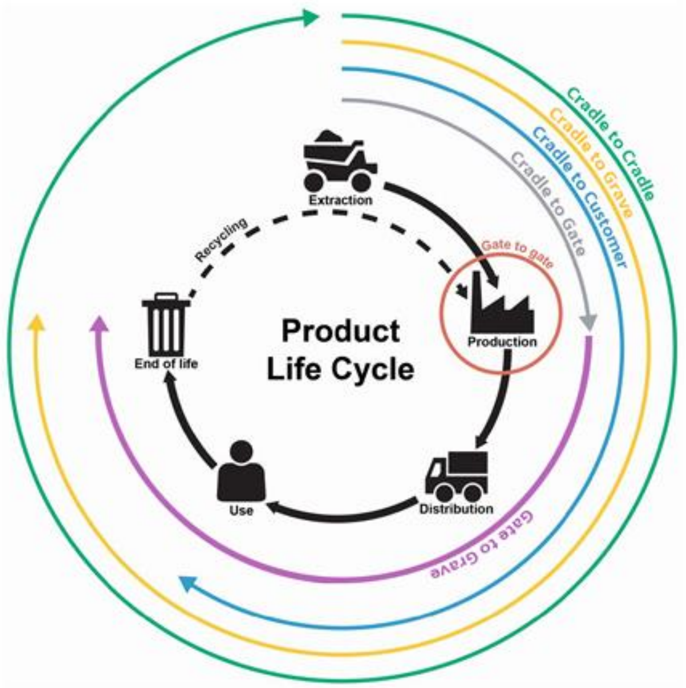


Figure 4.3 Product life cycle and six approaches of defining a system boundary[59]

The cradle-to-grave approach is defined as a full LCA, from resource extraction, "cradle," to the use phase, and finally the disposal phase, "grave" [59].

A cradle-to-cradle assessment is an alternative cradle-to-grave approach that takes recycling into account [59].

The Cradle-to-Gate technique assesses a product's life cycle from the extraction of raw materials (the "cradle") to the point of factory exit, which comes before the product is delivered to the customer. Phases that deal with product usage and disposal are usually left out. environmental product declarations (EPDs) are sometimes based on cradle-to-gate evaluations [59].

The gate-to-gate evaluation focuses on a certain stage of the product life cycle, from the start of manufacturing operations to the factory gate. It includes all inputs and outputs from each production stage at the factory. As a result, a gate-to-gate LCA investigates only one value-added step from the full production chain [59].

The Cradle-to-Customer method assesses the environmental impacts of obtaining raw materials, manufacturing, trading, and delivering consumer goods and services to the end user. This methodology involves the addition of data on transportation routes and the type of energy used in these activities[59].

4.2 LCA Standards

Since the 1990s, national standardization organizations and, particularly, ISO have made significant efforts to standardize life cycle assessments. Prior to ISO 14040, only two national standardization organizations produced their own LCA standards: AFNOR (Association Française de Normalization, France) and CSA (Canadian Standards Association, Canada). France and Canada have joined the ISO process to promote worldwide communication through a single standard [58]. Today, the International Organization for Standardization (ISO) offers principles and a framework via ISO 14040, along with guidelines and requirements through ISO 14044.

During the ISO standardization process in the 1990s, the LCA technique was relatively new and underdeveloped. As a result, the resulting guidelines lack precise requirements on specific methodological options, focusing instead on the framework and basic principles of LCA [55].

4.3 LCA Phases

According to ISO 14040 &14044 the LCA framework consists of four stages:

- Goal and scope definition
- Life cycle inventory analysis (LCI) phase
- Life cycle impact assessment (LCIA) phase
- Interpretation

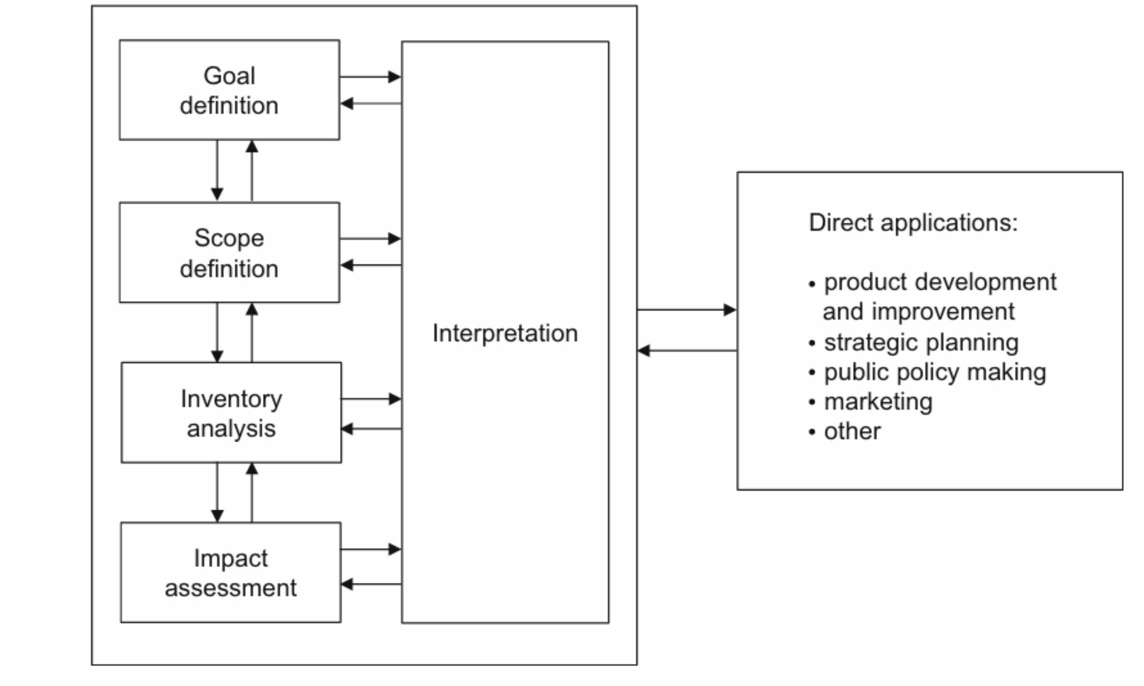


Figure 4.4 LCA framework modified from the ISO 14040 standard.

These phases provide an iterative process in which the outcome of one stage influences the results of the previous stages. The idea is that performing the LCA increases knowledge of the system, resulting in better assumptions and an overview of which factors and activities should be included inside the system boundary [1].

4.3.1 Goal and scope definition

Defining the goals and scope is the first stage of an LCA which is considered as the most important phase since it establishes the research context, establishes requirements for the modelling that will be done, and plans the project. This is known as the planning phase and is the initial phase of LCA research. Therefore, it is crucial for design practitioners to select the appropriate initial step when introducing LCA into the product design and development processes [55].

The ISO standard highlights that an LCA's scope is determined by its goal. The LCA focuses on the natural environment, human health, and resource utilization, and the standard does not include economic assessments as part of an LCA, however, it encourages the use of additional life cycle studies, such as cost analysis [1].

An LCA's iterative structure allows for additional refinement of the scope during the study [60]. Several arrows in Figure 4.4 indicate that, rather of following a linear process, LCA incorporates multiple feedback loops between its various phases. The impact assessment provides insights that help refine the inventory analysis, and both phases may influence the scope definition. For example, they can influence decisions regarding what to include and exclude when defining the boundaries of the product system. Typically, the initial iteration involves a screening of the entire life cycle. However, inventory data is generally based on readily available databases [55].

ISO 14044 requires four aspects of the study to be properly mentioned when defining its goal. The standard defines the function of the product as the defining feature of the system under examination [1], [55] :

- Intended Applications of the Results.

LCAs analyse product systems and can be applied to several purposes, including:

  - Evaluating the environmental effects of particular products or services.
  - Identifying the aspects of a product system that have the biggest impact on its environmental footprint.
  - Assessing the opportunities for improvement through changes in product design.
  - Developing policies that consider environmental concerns.

- Reasons for conducting the study.

The goal definition plays a significant role in developing an adequate life cycle inventory.

- Target Audience

The goal definition should identify the intended audience for communicating the study's results. The target audience may include consumers, consumer organizations, or companies (managers, product developers, etc.), government, non-governmental organizations (NGOs), and others. The study's intended audience greatly impacts the level of documentation and technical reporting required, also have the results should be interpreted.

- Comparative Studies to Be Made Public.

The goal definition should make it clear whether the LCA study is comparative in nature and whether it is meant to be made public. If so, the ISO standard specifies specific requirements for the study's execution and documentation, as well as an external evaluation mechanism. This is due to the possible impact of disseminating the study's findings on external entities such as businesses, institutions, customers, and stakeholders.

Furthermore, the design practitioners are required to pinpoint four essential tasks throughout the goal and scope definition stage: (1) define a functional unit, (2) create a system boundary, (3) choose the type of environmental impacts, and (4) Choosing the level of complexity and required data for the study’s aim [59].

The functional unit serves as a reference for the inputs and outputs of the product being researched. For an OWT, a sensible functional unit could be the amount of produced energy, such as MWh. All inputs and outputs from the life cycle inventory analysis (LCI) and life cycle impact assessment (LCIA) should be linked to this unit. The functional unit determines the metric under examination in the LCA and is critical throughout the goal and scope definition stage[1].

In this step, the system boundary is also determined. The system boundaries describe what is included and ignored in the assessment. Tiny quantities of substances might be excluded from the analysis because their impact on the overall footprint is negligible [59].

The unit processes that need to be included in the LCA are specified by the system boundary. The smallest processes taken into account in the life cycle inventory analysis (LCI) are called unit processes [1].

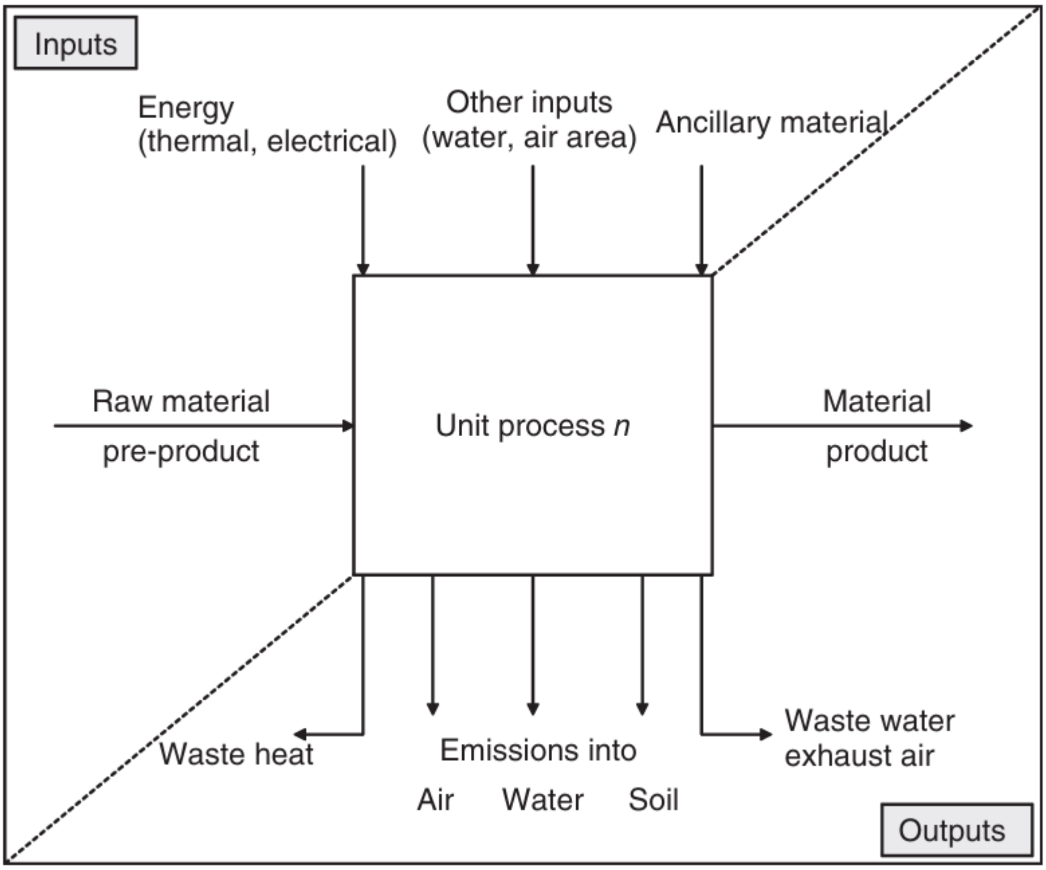


Figure 4.5 Schematic illustration of a unit process [58]

Figure 4.6 depicts the system environment, which is made up of components such as processes, input and output streams that are contained within the system's boundary. These streams are classified as product and elementary flows. Product flows originate in this system or in other systems, whereas elementary flows include resource use and emissions [1].

Figure 4.6 shows a product system that covers the complete life cycle, from manufacturing to downstream and upstream operations. So, it includes a wide boundary. However, depending on the LCA goal and restrictions, the boundary may become narrower, leading to assumptions [59].

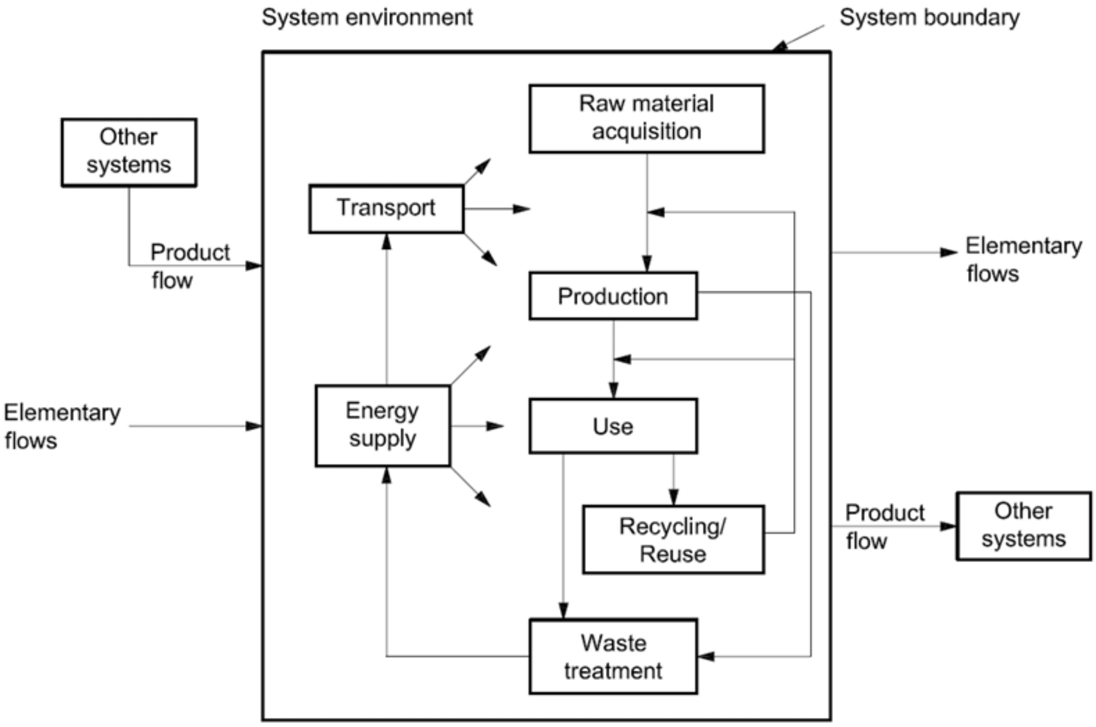


Figure 4.6 Illustration of system environment in ISO 14040 [57]

4.3.2 Life cycle inventory analysis (LCI)

ISO 14040 define LCI as:

> *“Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its entire life cycle.”*

LCI is the second step and frequently, the most time-consuming part of an LCA. The output is an inventory of elementary flows, which serves as the foundation for the life cycle impact assessment. LCI analysis can done with six steps below [55]:

1- Identifying processes to incorporate into the LCI model.
2- Planning and gathering data.
3- Building and verifying unit processes for accuracy.
4- Creating the LCI model and computing LCI results.
5- Establishing the basis for managing uncertainties and conducting sensitivity analysis.
6- Reporting.

Data are gathered for each unit process under evaluation. Data may include energy inputs, raw materials, emissions, and waste. The calculation step relates the gathered data to the unit process and functional unit. During this step, it is critical to validate the obtained data. This validation procedure ensures that the data meets the expected depth and breadth, as defined in the aim and scope definitions[1].Figure 4.7 shows the flow chart of a LCI process taken from the ISO 14044 standard.

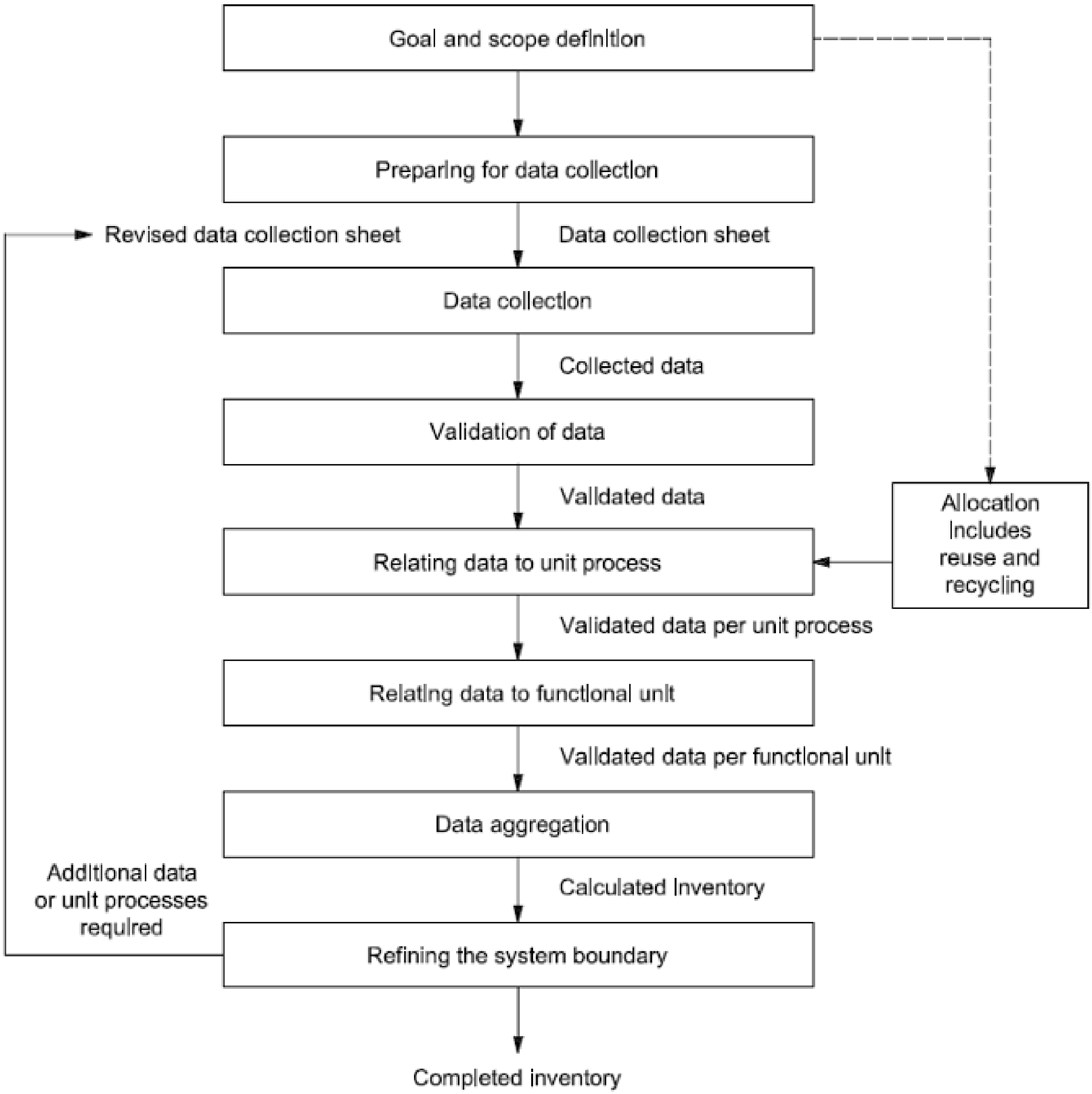


Figure 4.7 Overview of the LCI process, taken from the ISO 14044 standard.

4.3.3 Life Cycle Impact Assessment (LCIA)

The third phase of an LCA study is LCIA where the life cycle inventory's data regarding elementary flows is converted into scores reflecting environmental impacts. Typically, the LCIA stage is completely automated, with the practitioner picking an LCIA technique and a few more parameters using menus and buttons in LCA software. However, as simple as it may look, without understanding a few key principles and the meaning of the indicators, it is impossible to make an informed choice of LCIA technique or accomplish a meaningful and reliable interpretation of LCA results. The ISO 14040/14044 standards delineate mandatory and optional stages for the LCIA phase. These steps are depicted in Figure 4.8 [55].

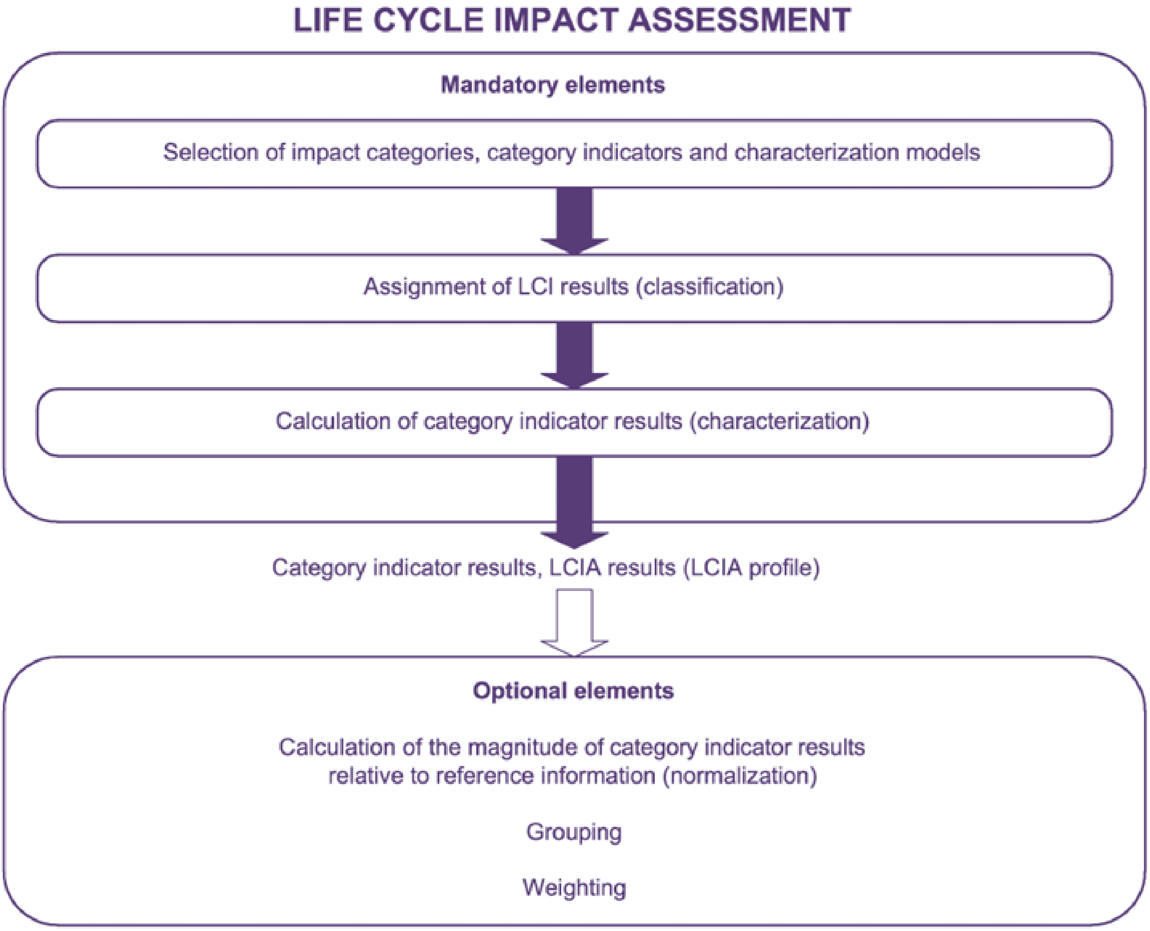


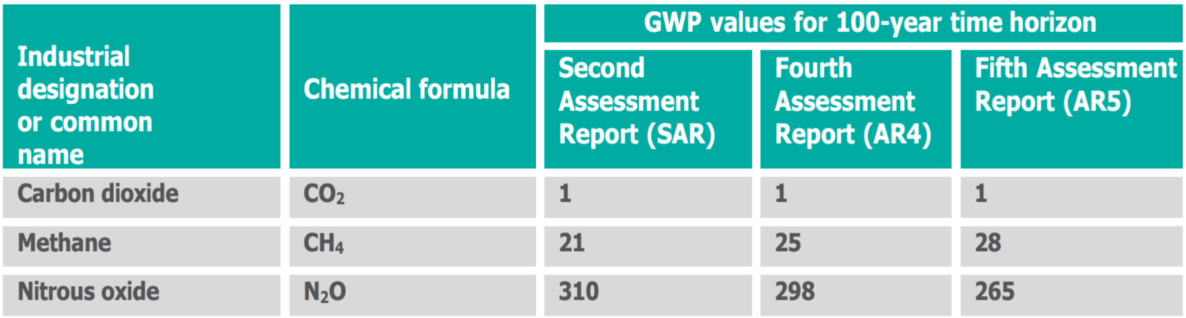
Figure 4.8 LCIA phases [60]

Emissions vary in form and structure since emissions from raw material extraction differ greatly from those from energy generation. This is where impact categories become useful. The LCIA of an LCA attempts to incorporate these various emissions into useful indicators. In other words, emissions having similar consequences are combined into a single unit assigned to a specific impact category[59].

The Global Warming Potential (GWP) is the most widely recognized impact category. The climate change is mostly impacted by greenhouse gas emissions other than carbon dioxide (CO_2), such as methane (CH_4) and nitrous oxide (N_2O), also known as laughing gas. A climate change impact category helps to create a consistent metric by converting non-CO_2 greenhouse gas (GHG) emissions into kilograms of CO_2 equivalents ($kgCO_2e$) using alternative measurement units [59]. The Global Warming Potential (GWP) of a greenhouse gas measures its ability to affect the Earth's radiation balance. It is quantified in terms of a reference material, typically CO_2-equivalent units, and specific time periods such as GWP 20, GWP 100, and GWP

500, which correspond to 20, 100, and 500 years, respectively. This factor corresponds to the project's ability to influence the world average surface-air temperature and other climate factors [40].

Table 4.1 The global warming potential of common greenhouse gases in 100 year time horizon [61]

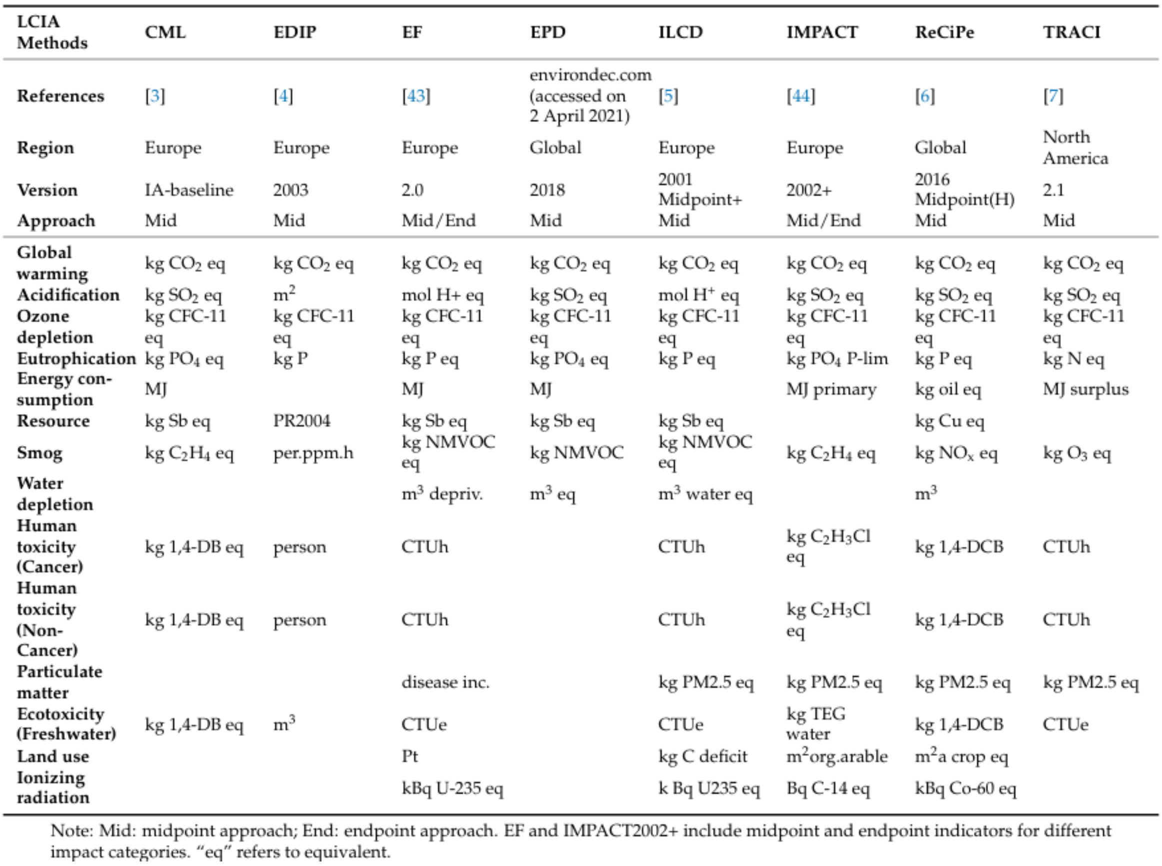


Industrial designation or common name	**Chemical formula**	**GWP values for 100-year time horizon**		
		Second Assessment Report (SAR)	**Fourth Assessment Report (AR4)**	**Fifth Assessment Report (AR5)**
Carbon dioxide	**CO_2**	**1**	**1**	**1**
Methane	**CH_4**	**21**	**25**	**28**
Nitrous oxide	**N_2O**	**310**	**298**	**265**

4.3.3.1 Life Cycle Impact Assessment (LCIA) models

Several life cycle impact assessment (LCIA) models have been developed and used to assess the environmental impacts of products and activities, including: ReCiPe (Resource Use, Emissions, and Health Impacts), IMPACT (Integrated Methodology for Impact Assessment of Chemicals, CML (Centre for Environmental Studies), Eco-indicator, EPS (Environmental Priority Strategies), USEtox (Unified System for the Evaluation of Toxicity), TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts). These examples are simply a sample of the several LCIA models available. Each model has distinct strengths, limitations, and areas of special emphasis [59]. ISO 14044 [42] also states that these models must be "internationally recognized" and based on "international agreement." Many intergovernmental organizations have developed their own frameworks for analysing environmental effect. LCAs for offshore wind projects have used a range of methodologies [1].

Each LCA impact category is associated with a specific unit, which may differ between models, as shown in Figure 4.9. However, for the purpose of discussion or comparison, these units might be reduced to a single score or point [62].



LCIA Methods	**CML**	**EDIP**	**EF**	**EPD**	**ILCD**	**IMPACT**	**ReCiPe**	**TRACI**
References	[3]	[4]	[43]	environdec.com (accessed on 2 April 2021)	[5]	[44]	[6]	[7]
Region	Europe	Europe	Europe	Global	Europe	Europe	Global	North America
Version	IA-baseline	2003	2.0	2018	2001 Midpoint+	2002+	2016 Midpoint(H)	2.1
Approach	Mid	Mid	Mid/End	Mid	Mid	Mid/End	Mid	Mid
Global warming	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq
Acidification	kg SO_2 eq	m^2	mol H+ eq	kg SO_2 eq	mol H^+ eq	kg SO_2 eq	kg SO_2 eq	kg SO_2 eq
Ozone depletion	kg CFC-11 eq	kg CFC-11 eq	kg CFC-11 eq	kg CFC-11 eq	kg CFC-11 eq	kg CFC-11 eq	kg CFC-11 eq	kg CFC-11 eq
Eutrophication	kg PO_4 eq	kg P	kg P eq	kg PO_4 eq	kg P eq	kg PO_4 P-lim	kg P eq	kg N eq
Energy consumption	MJ		MJ	MJ		MJ primary	kg oil eq	MJ surplus
Resource	kg Sb eq	PR2004	kg Sb eq	kg Sb eq	kg Sb eq		kg Cu eq	
Smog	kg C_2H_4 eq	per.ppm.h	kg NMVOC eq	kg NMVOC	kg NMVOC eq	kg C_2H_4 eq	kg NO_x eq	kg O_3 eq
Water depletion			m^3 depriv.	m^3 eq	m^3 water eq		m^3	
Human toxicity (Cancer)	kg 1,4-DB eq	person	CTUh		CTUh	kg C_2H_3Cl eq	kg 1,4-DCB	CTUh
Human toxicity (Non-Cancer)	kg 1,4-DB eq	person	CTUh		CTUh	kg C_2H_3Cl eq	kg 1,4-DCB	CTUh
Particulate matter			disease inc.		kg PM2.5 eq	kg PM2.5 eq	kg PM2.5 eq	kg PM2.5 eq
Ecotoxicity (Freshwater)	kg 1,4-DB eq	m^3	CTUe		CTUe	kg TEG water	kg 1,4-DCB	CTUe
Land use			Pt		kg C deficit	m^2org.arable	m^2a crop eq	
Ionizing radiation			kBq U-235 eq		k Bq U235 eq	Bq C-14 eq	kBq Co-60 eq	

Note: Mid: midpoint approach; End: endpoint approach. EF and IMPACT2002+ include midpoint and endpoint indicators for different impact categories. “eq” refers to equivalent.

Figure 4.9 LCIA methodologies and impact categories [62].

4.3.3.1.1 The ReCiPe model

LCIA uses characterization factors to convert emissions and resource extraction into a limited number of impact scores. ReCiPe computes two types of indicators while determining these characterisation factors: 18 midpoint indicators and 3 endpoint indicators [59]. This approach deals with various environmental issues at the midpoint level and subsequently consolidates these midpoints into three Endpoint categories. Figure 4.1 and Table 4.2 shows midpoints and endpoints indicators covered by ReCiPe model respectively.

Endpoint indicators indicate the environmental impact at higher levels of aggregation, such as human health, biodiversity, and resource scarcity. While midpoint approaches evaluate an effect before any damage is done to one of the areas of protection, endpoint methods track the effects of specific emissions until they create harm [59].

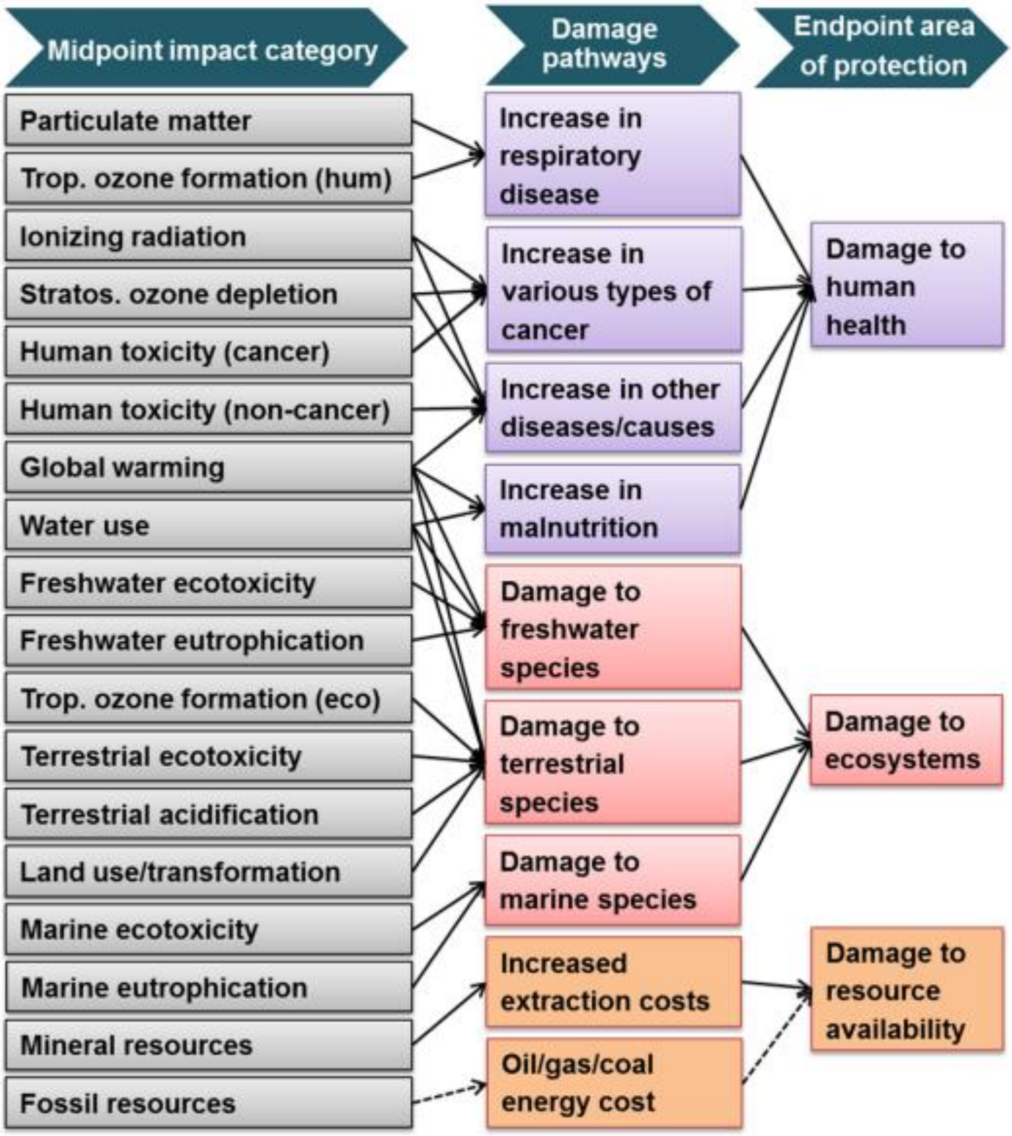


Figure 4.10 Midpoints indicators covered by ReCiPe model [54].

Table 4.2 Endpoint indicators covered by ReCiPe model [63]

Area of protection	**Endpoint**	**Abbr.**	**Name**	**Unit**
human health	damage to human health	HH	disability-adjusted loss of life years	year
natural environment	damage to ecosystem quality	ED	time-integrated species loss	species ×yr
resource scarcity	damage to resource availability	RA	surplus cost	Dollar

4.3.4 Interpretation

The interpretation stage is the last phase of an LCA, during which the results of the previous phases are combined and evaluated in light of the uncertainties inherent in the data and the documented assumptions created during the study [55].According to ISO 14040 and ISO 14044 standards, the interpretation phase should include several key components. These include identifying key issues based on the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) results, determining completeness, sensitivity, and consistency, drawing conclusions, defining limitations, and making recommendations. Moreover, it may involve requesting re-evaluation following adjustments or the availability of updated information or data [59].The interpretation progresses through three stages as depicted in Figure 4.11 [55].The ISO standards stress that the interpretation phase should concentrate on the uncertainties in the results, especially from the LCI [1].

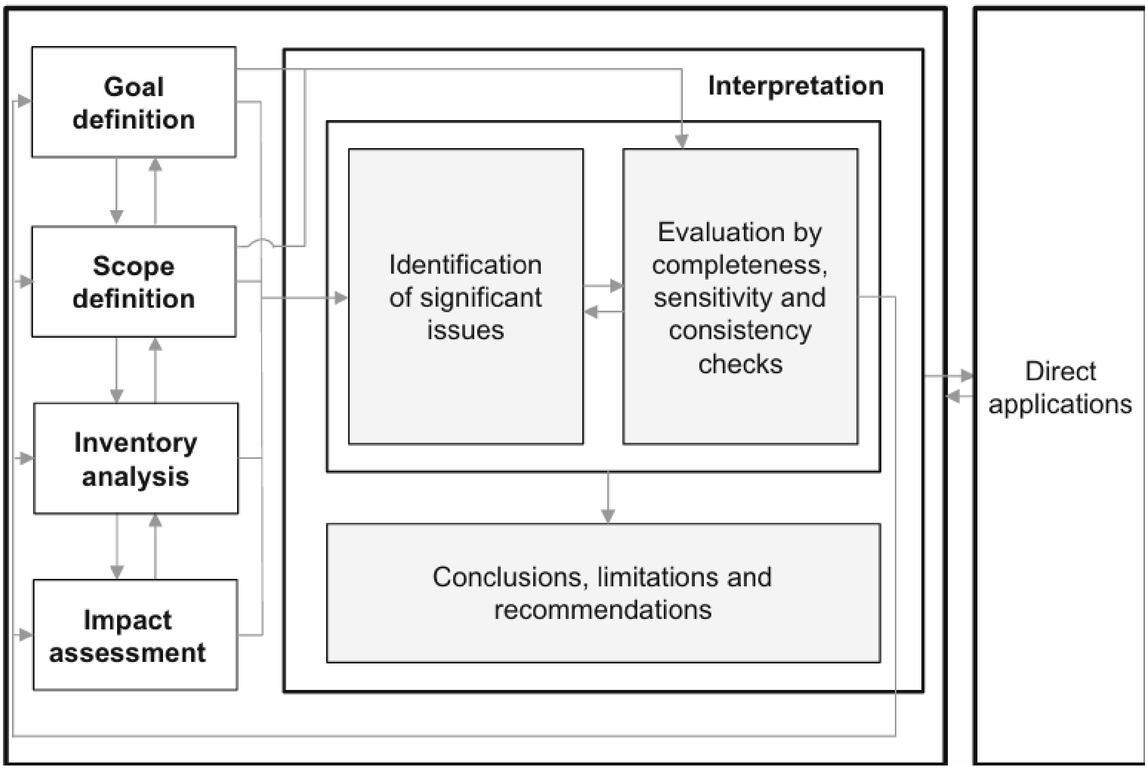


Figure 4.11 The components of the interpretation stage and how they interact with one another and with the other LCA phases [55].

4.4 Software and Database

4.4.1 OpenLCA® Software

Unlike alternative tools, openLCA®, developed by GreenDelta, is an open-source software. It provides a rapid, dependable, high-performance, flexible platform for sustainability evaluation and life cycle modeling. openLCA® offers visually appealing and adaptive modeling, allowing both complex and simple models, all inside a standard programming language and with easily available open-source tools. GreenDelta, headquartered in Berlin, receives support from an initial funding consortium as well as several research and industry projects. These projects include the Horizon Europe funding program, the European Union's research and innovation initiative that runs from 2021 to 2027 [64].

To describe a product's life cycle, the software uses four major categories: flow, process, product system, and project. Flow describes how products, materials, or energy move between processes. A process is a sequence of activities that convert inputs into outputs. A product system is a collection of procedures, and projects allow you to compare different product systems [65].

4.4.2 Ecoinvent Database

Accessing the entire supply chain is crucial during an LCA. Gathering such data manually is practically impossible, but databases like ecoinvent enable LCA practitioners to focus on foreground data (the system's inputs and outputs) while relying on background datasets [59].

The ecoinvent Association is a non-profit organization established in Zurich, Switzerland, dedicated to supplying high-quality data for sustainability evaluations worldwide [66].
The ecoinvent database currently contains over 18,000 reliable life cycle inventory datasets, which are updated annually to include new and amended data as well as technical upgrades. ecoinvent data, which prioritizes transparency, traceability, and extensive breakdowns, makes it easier to do global environmental evaluations such as carbon footprinting, LCA, and environmental product declarations (EPDs). It enables various users to better understand the environmental impacts of their products and services [66].
The ecoinvent database assigns a particular geographic location to each activity. These geographic locations, often known as 'geographies,' are denoted in the dataset's name with internationally recognized acronyms. As a foundational database, the ecoinvent Database seeks to include activities in the most relevant places for the chosen product or service. However, the breadth of geographic coverage is determined on the quality and availability of data [59].

Additional databases also exist, such as the EU & DK Input-Output database, which is particularly intended for products commonly imported into the EU, and the CEDA database, which was produced by the Vital-Metrics group [1].

5 Performing LCA of Offshore Wind Farms

In this chapter, the methodology used to conduct the LCA study is presented. This study uses process based LCA methodology following ISO 14040 &14044 LCA framework, general requirements, and guidelines which have been discussed in Chapter 4.

5.1 Defining the Goal

The goals of this study were to:

- Assessing the environmental impact of different stages in the lifecycle of the two real case floating and bottom fixed offshore wind farms. (Dogger Bank (C) and Hywind Tampen)
- Identifying the key elements affecting the environmental impact of offshore wind projects.
- Learning about potential opportunities for environmental optimization throughout the life cycle of offshore wind projects.
- Evaluating the validity of LCA findings and identifying relevant areas for future research.

5.2 Defining the Scope

During this step, functional unit and system boundaries are defined.

5.2.1 Functional Unit (FU)

The defined functional unit (FU) in this study is 1 MWh of electricity produced by the wind farm throughout its life cycle and subsequently delivered to the grid. This functional unit was chosen to ensure a fair comparison of the environmental impacts between the two OWFs in this study and facilitate comparison of the results with existing literature and other energy sources.

5.2.2 System Boundaries

The scope of this study is cradle-to-grave and an overview of the defined system boundaries for the current LCA have been illustrated in Figure 5.1. Due to high levels of uncertainty and issues with the availability of the data, recycling was not considered as a part of End of Life (EOL) stage in the current study and as can be seen in Figure 5.1 it is outside of the system boundaries. As mentioned earlier, if recycling was considered, the LCA method would become a cradle-to-cradle method.

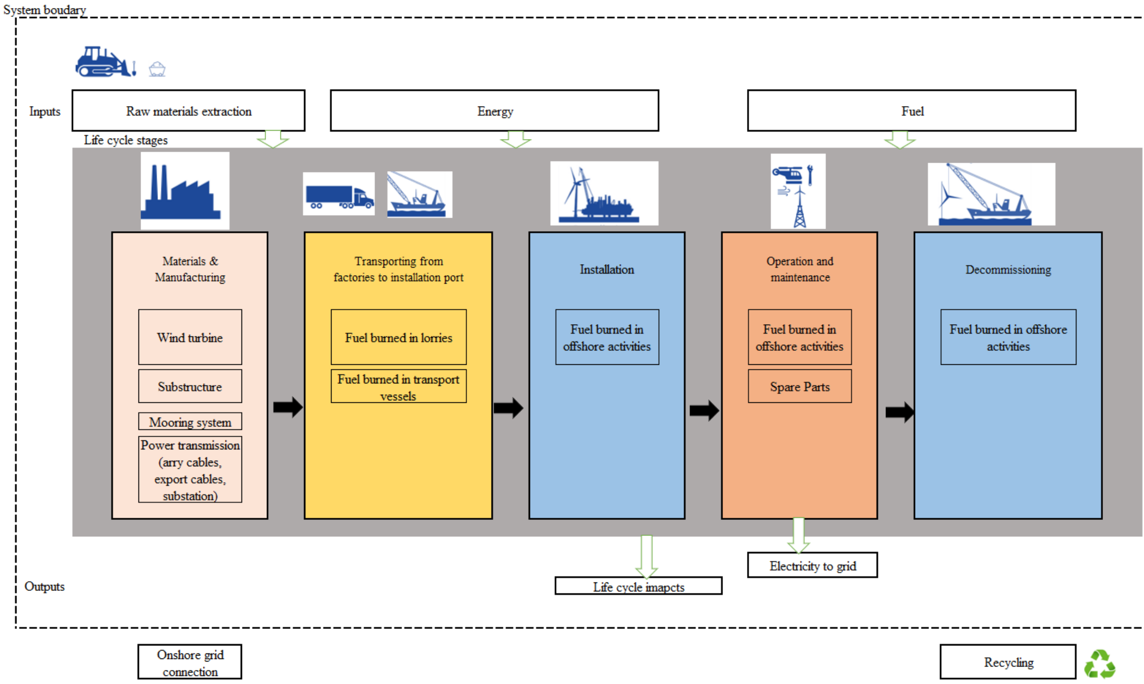


Figure 5.1 An overview of the defined system boundaries for the current LCA, inspired from [8]

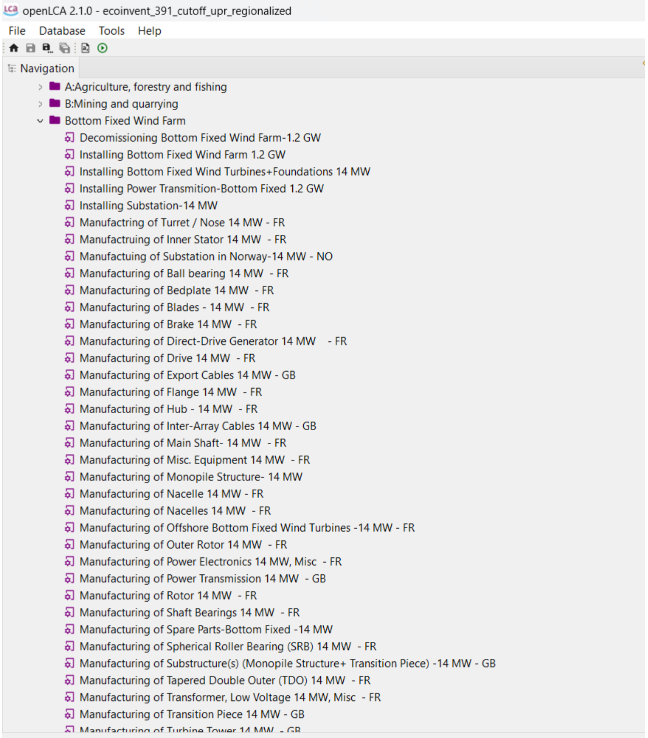
5.3 Life Cycle Inventory Analysis (LCI)

As mentioned previously, Life Cycle Inventory (LCI) is the second step and often proves to be the most time-intensive phase of an LCA. In this step, data were gathered for each unit process under evaluation. Data include energy inputs, raw materials, and emissions. These inputs and outputs were used as flows in each unit process and modelled in the openLCA® software. Due to the importance of this step of LCA, chapter 6 has been allocated to it and detailed information on calculations and data gathering are provided in the mentioned chapter.

5.4 Life Cycle Impact Assessment (LCIA)

5.4.1 Software and database

The openLCA® version 2.1 together with ecoinvent 3.9 database were used to conduct LCIA. Due to the complexity of manufacturing of OWFs, many unit processes were created in the openLCA® software, and the output of each unit process was connected to the next unit process with proper flows. A screenshot of some created unit processes in the software has been shown in Figure 5.2.



A:Agriculture, forestry and fishing
B:Mining and quarrying
Bottom Fixed Wind Farm
Decomissioning Bottom Fixed Wind Farm-1.2 GW
Installing Bottom Fixed Wind Farm 1.2 GW
Installing Bottom Fixed Wind Turbines+Foundations 14 MW
Installing Power Transmition-Bottom Fixed 1.2 GW
Installing Substation-14 MW
Manufactring of Turret / Nose 14 MW - FR
Manufactruing of Inner Stator 14 MW - FR
Manufactuing of Substation in Norway-14 MW - NO
Manufacturing of Ball bearing 14 MW - FR
Manufacturing of Bedplate 14 MW - FR
Manufacturing of Blades - 14 MW - FR
Manufacturing of Brake 14 MW - FR
Manufacturing of Direct-Drive Generator 14 MW - FR
Manufacturing of Drive 14 MW - FR
Manufacturing of Export Cables 14 MW - GB
Manufacturing of Flange 14 MW - FR
Manufacturing of Hub - 14 MW - FR
Manufacturing of Inter-Array Cables 14 MW - GB
Manufacturing of Main Shaft- 14 MW - FR
Manufacturing of Misc. Equipment 14 MW - FR
Manufacturing of Monopile Structure- 14 MW
Manufacturing of Nacelle 14 MW - FR
Manufacturing of Nacelles 14 MW - FR
Manufacturing of Offshore Bottom Fixed Wind Turbines -14 MW - FR
Manufacturing of Outer Rotor 14 MW - FR
Manufacturing of Power Electronics 14 MW, Misc - FR
Manufacturing of Power Transmission 14 MW - GB
Manufacturing of Rotor 14 MW - FR
Manufacturing of Shaft Bearings 14 MW - FR
Manufacturing of Spare Parts-Bottom Fixed -14 MW
Manufacturing of Spherical Roller Bearing (SRB) 14 MW - FR
Manufacturing of Substructure(s) (Monopile Structure+ Transition Piece) -14 MW - GB
Manufacturing of Tapered Double Outer (TDO) 14 MW - FR
Manufacturing of Transformer, Low Voltage 14 MW, Misc - FR
Manufacturing of Transition Piece 14 MW - GB
Manufacturing of Turbine Tower 14 MW - GB

Figure 5.2 A screenshot of some unit processes created in openLCA® to model Dogger Bank BFOWF

5.4.2 Impact assessment method

The ReCiPe 2016 v1.03, midpoint (H) methodology was chosen to match with current energy and environmental policies that aim to improve transparency and comparability [8]. Most available research uses this method; therefore, this study utilized the same method to ensure comparability of the results.

5.5 Interpretation and Reporting

According to ISO 14040 and ISO 14044, the interpretation phase should include the following actions: Identifying key issues based on the results of the life cycle inventory (LCI) and life cycle impact assessment (LCIA), analyzing completeness, sensitivity, and consistency, drawing conclusions, outlining limitations, and making suggestions [59]. In the results and discussion Chapter these actions have been addressed.

6 Basic Calculations and Data Collection

In this study, two base cases were established, one for BFOWF and one for FOWF. The rationale behind choosing these base cases is that these two use the most recent technologies and largest turbine sizes in offshore wind. These base cases served as a reference point for comparisons, aiming to pinpoint the primary factors influencing environmental impacts.

6.1 BFOWF Base Case: Dogger Bank C Wind Farm

The Dogger Bank Wind Farm is divided into three phases, Dogger Bank A, B, and C, and it is located between 130km to 190km off England's Northeast coast. Together, they will comprise the world's largest offshore wind farm. Each phase will have a capacity of 1.2 GW, with large multibillion-pound investments. They will have a total capacity of 3.6 GW, which is enough to power about 6 million households each year. Dogger Bank C has an installed generation capacity of 1.2GW and a development area of approximately 560 square kilometres with water depths ranging from 18m to 63. The 87 wind turbines used for this BFOWF are Haliade-X 14 MW made by General Electrics [67]. Table 6.1 describes the technical specifications of this giant wind turbine.

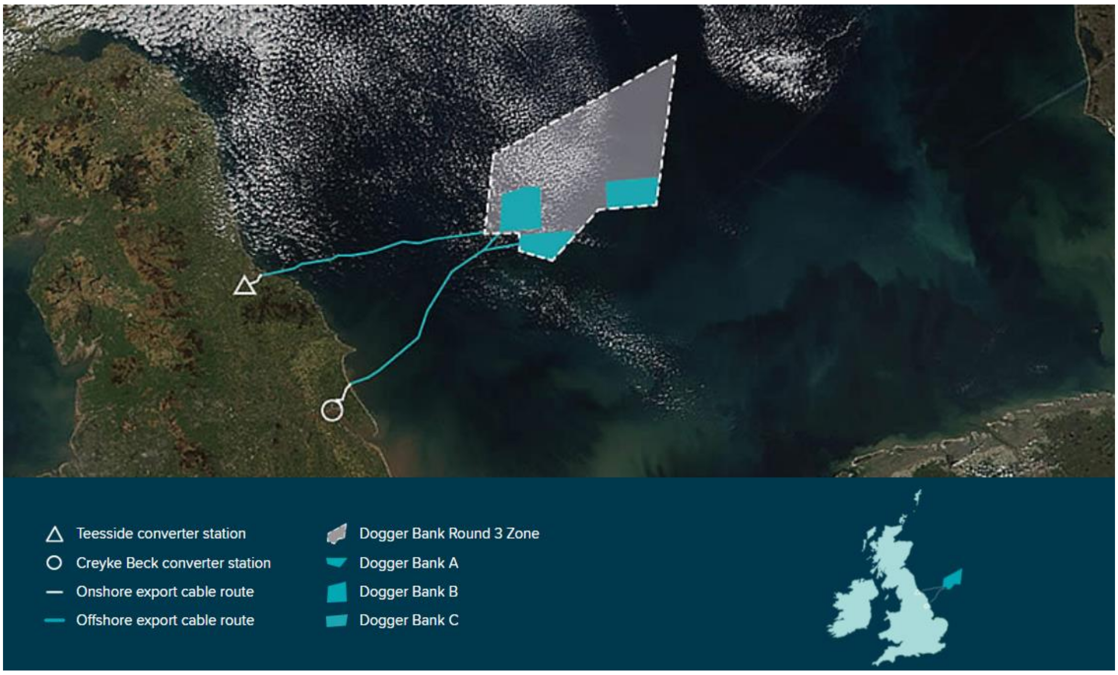


Figure 6.1 The Dogger Bank wind farm layout [67].

Table 6.1 Haliade-X 14 MW technical specifications [68].

Specification	Value
Output (MW)	14
Rotor diameter (m)	220
Total height (m)	up to 260
Frequency (Hz)	50 & 60
Gross AEP (GWh)	~74
Capacity Factor (%)	60-64
IEC Wind Class	IC

Haliade-X 14 MW is the most potent offshore turbine ever constructed. To understand its magnitude this turbine is compared with some well-known monuments in Figure 6.2 [69].

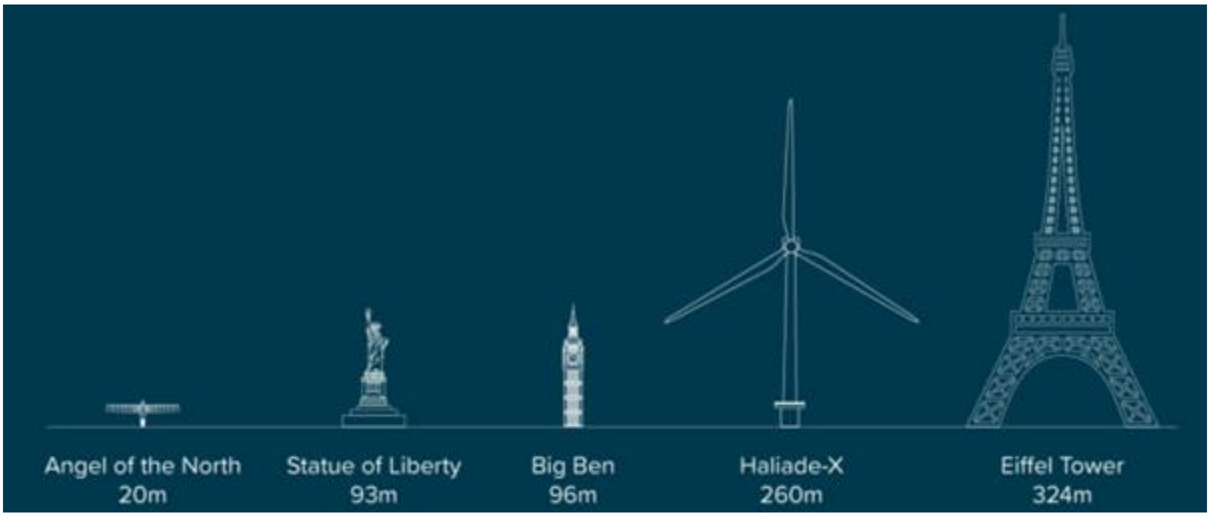


Figure 6.2 Comparing the size of Haliade-X 14 MW with some well-known monuments [69].

6.2 FOWF Base Case: Hywind Tampen Wind Farm

Hywind Tampen is the world's first floating wind farm developed exclusively for powering offshore oil and gas installations. It is now supplying electricity to Equinor's Snorre and Gullfaks oil and gas fields in Norway's North Sea. With a capacity of 88 MW, it is also the largest floating offshore wind farm in the world, indicating significant progress in industrializing solutions and lowering costs for future offshore wind projects. Hywind Tampen serves to advance floating wind technology by experimenting with new and larger turbines, installation procedures, simplified moorings, concrete substructures, and gas-wind integration. The farm comprises 11 wind turbines that have been upgraded from 8 to 8.6 megawatts each. It is expected to meet around 35% of the yearly electricity consumption for the five Snorre A and B, and Gullfaks A, B, and C platforms. During periods of stringer winds, this fraction is predicted to rise dramatically [70]. Figure 6.3 and Figure 6.4 illustrate the location and layout of the Hywind Tampen wind farm respectively.

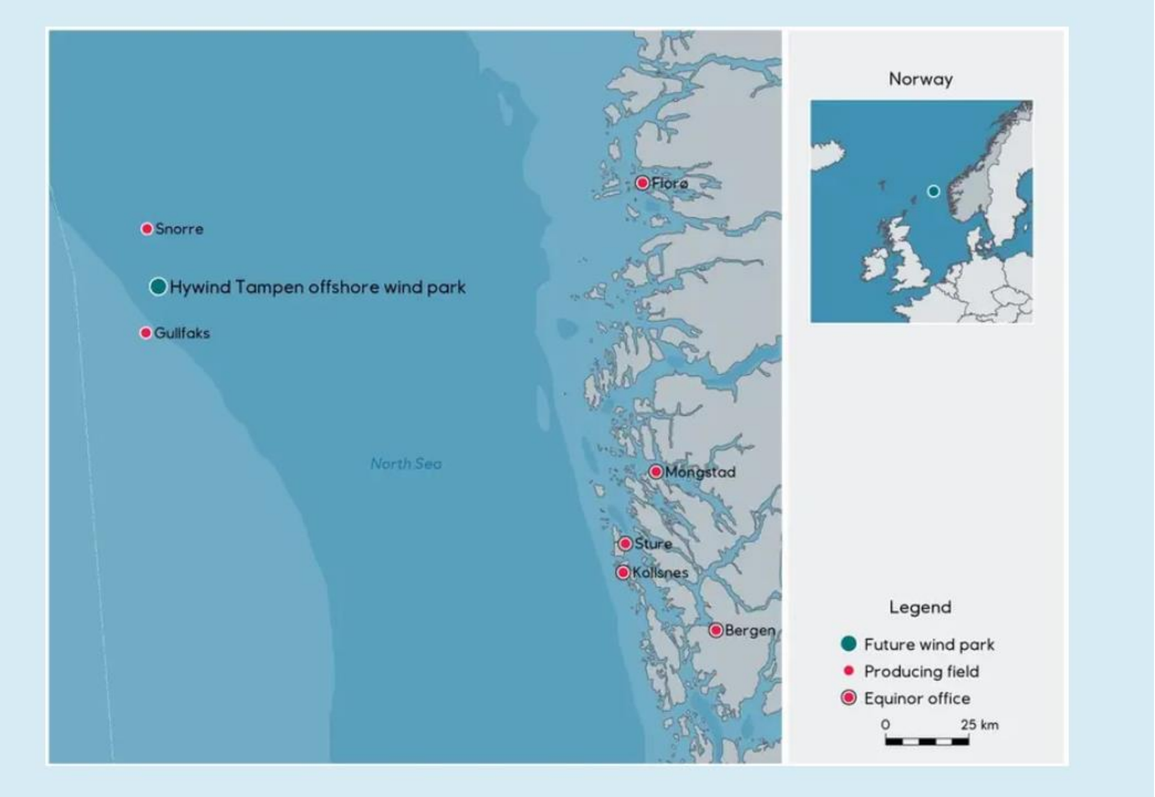


Figure 6.3 Hywind Tampen FOWF location [70].

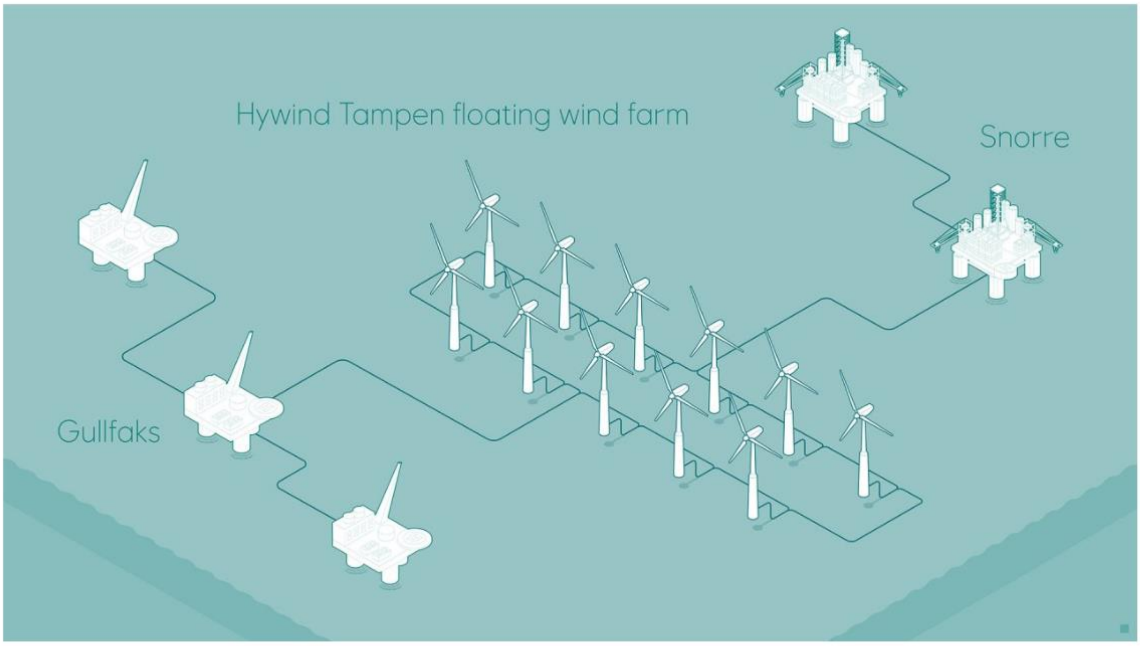


Figure 6.4 Hywind Tampen FOWF layout [71].

To collect data regarding wind turbine size, foundation type, capacity factor, cables, etc. various sources, and reports were investigated, the summary of these data is provided in Table 6.2. Due to lack of data, some assumptions were made which are described accordingly.

Table 6.2 Specifications of the two selected base cases

Specification	**Bottom fixed**	**Floating**
Wind Farm Name	Dogger Bank (C)	Hywind Tampen
Distance to port (km)	130 [69]	140 [70]
Power of each turbine (MW)	14 [68]	8 [70]
Number of turbines	87 [69]	11 [70]
Turbine Nominal Capacity Factor (%)	64 [68]	Data not available
Wind Farm Capacity Factor (%)	45.3[4]	54% (assumed the same as Hywind Scotland) [73]
Generator type	Direct Drive [68]	Direct Drive [71]
Lifetime (years)	20	20 [74]
Foundations	Monopile [75]	concrete SPAR-type (ballast-stabilized and anchored to the seabed with mooring lines)
Turbine Manufacturer Company	GE [68]	Siemens Gamesa [76]
Turbine Model Name	Haliade-X 14 MW [68]	SG 8.0-167 DD [76]
Tower Length (m)	150 [68]	92 [74]
Rotor Diameter (m)	220 [68]	167 [74]
Total Height (m)	260 [68]	175 [74]
Distance between the turbines (km)	2.8 [77]	1.5 [71]
Water depth (m)	18-63 (this study assumes 30)[69]	200 [74]

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[4] As data for Dogger Bank C wind farm capacity factor were not available, the capacity factor of a nearby wind BFOWF was used [72].

6.3 Inventory Analysis

Inventory analysis is gathering data and running calculations to determine the product system's inputs and outputs. Inputs include energy, raw materials, and other products, whereas outputs include waste, water and air pollution, and any byproducts [1].These inputs and outputs were used as flows in each unit process and modelled in the openLCA® software. The data of the inventory were collected from below sources:

1- Available data on literature.

2- Reference wind turbines: Staff from the national renewable energy laboratory (NREL) and the technical university of Denmark (DTU) collaborated through the international energy agency (IEA) Wind Task 37 on Systems Engineering in Wind Energy to design the reference turbine. In recent years, reference wind turbines have grown in importance within the wind energy community, providing a variety of critical functions. Firstly, they serve as standard benchmarks with publicly available design criteria, establishing baselines for research into new technologies or design approaches. Second, because reference wind turbines are openly designed models, they allow industry stakeholders and external researchers to collaborate more effectively. Finally, they function as educational tools, providing a platform for beginners to wind energy to learn about core design principles and system tradeoffs [78].

3- Dogger Bank C and Hywind Tampen available environmental reports and documents.

4- Environmental product declarations (EPDs) from the international EPD System [79].

It is important to note that access to specific details of wind turbines and wind farms data is limited due to their commercial sensitivity. This lack of complete transparency necessitates certain assumptions when performing LCA of offshore wind farms.

In the following, inventory collection of each life cycle stages will be explained.

6.3.1 Materials and manufacturing

6.3.1.1 Tower and Nacelle

The raw material supply is simulated using market datasets from the ecoinvent database, which include both material acquisition and transportation to Europe [33].

Previous studies were either focused on smaller wind turbines or did not provide the inventory of their wind turbines. Some previous studies such as Bang et al. [40] and Garcia et al. [8] used regression based on information provided for other turbines to determine missing materials and weight distributions. This study assumes linear relationship between wind turbine size and the material weight distribution. Therefore, in order to determine the weights and materials of the 8 and 14 MW tower and nacelle ,linear interpolation of available inventories of 6 MW provided by Garcia et al. [8] and 15 MW reference wind turbine [78] was implemented. The reason why in this study other reference wind turbines' (5,8 and 10 MW) inventories were not used is the fact that these turbines have gearbox which doesn't apply to this study's direct-drive wind turbines.

The primary material used in the construction of the tower is low-alloyed steel [33].According to Siemens Gamesa EPD the 8 MW tower is 92 m in length, however, no data were provided for its diameter and wall thickness. The weight was obtained from linear interpolation .Also, the paint weight was negligible compared to other materials and were not taken into account [41].The same method applies to 14 MW wind turbines.

The welding length in some other studies was considered as a weld along the tower height [8], [33], however, this study considers that the tower is made of welded segments that each have 2 m height and peripheral length of the welded segments is taken into consideration. Figure 6.5 shows the welding process, and the Equation (6.1). shows the calculation method.

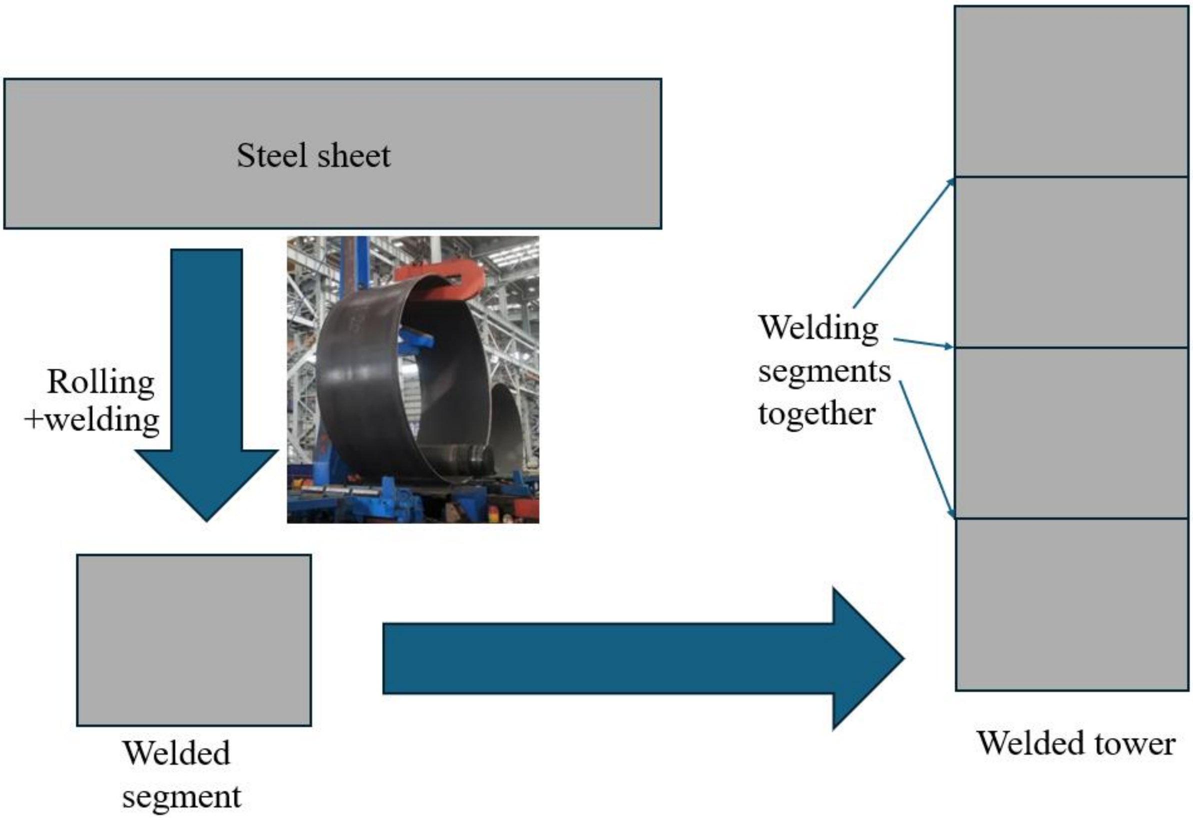


Figure 6.5 Tower manufacturing process.

$$L_W = L_T + N_s \times P \qquad (6.1)$$

Where L_W is the total welding length of the tower, L_T is the wind turbine tower's length, N_s is the number of segments of the tower and P is the perimeter of each segment. In case of 8 MW wind turbine, with diameter of 10 m the Lw is calculated as below. The tower length is 92 m and is made of 46 segments with each 2 m in length and 10 m in diameter.

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

With the same method the welding length of 14 MW wind turbine tower is calculated to be 2506 m.

The 8 main components of nacelle were modelled as separate unit processes in the openLCA® software, and some of them had subcategories that were modelled as separate unit processes as well. These components are described in the inventory list in Appendix F. For equipment that required machining the "Steel removed by turning, average, conventional {GLO}| market for | Cut-off, U" flow from ecoinvent database was chosen. The value of 0.23kg per kg of final product was assumed based on [8]. All other flow categories selected from the ecoinvent database for other materials and processes such as sheet rolling, casting, wire drawing, etc. are described in the inventory list in Appendix F.

6.3.1.2 Substructure

The material and weight of 8 MW turbine substructure were obtained from Siemens Gamesa EPD [80]. For 14 MW wind turbine, the same monopile substructure as 15 MW reference wind turbine wase assumed. The substructure of FOWT is made of three main components: spar structure and ballast. Welding length of the spar structure was calculated using Equation (6.1). On the other hand, the substructure of BFOWT is made of transition piece and monopile structure, and the concrete mass is negligible as a ballast in monopile foundation.

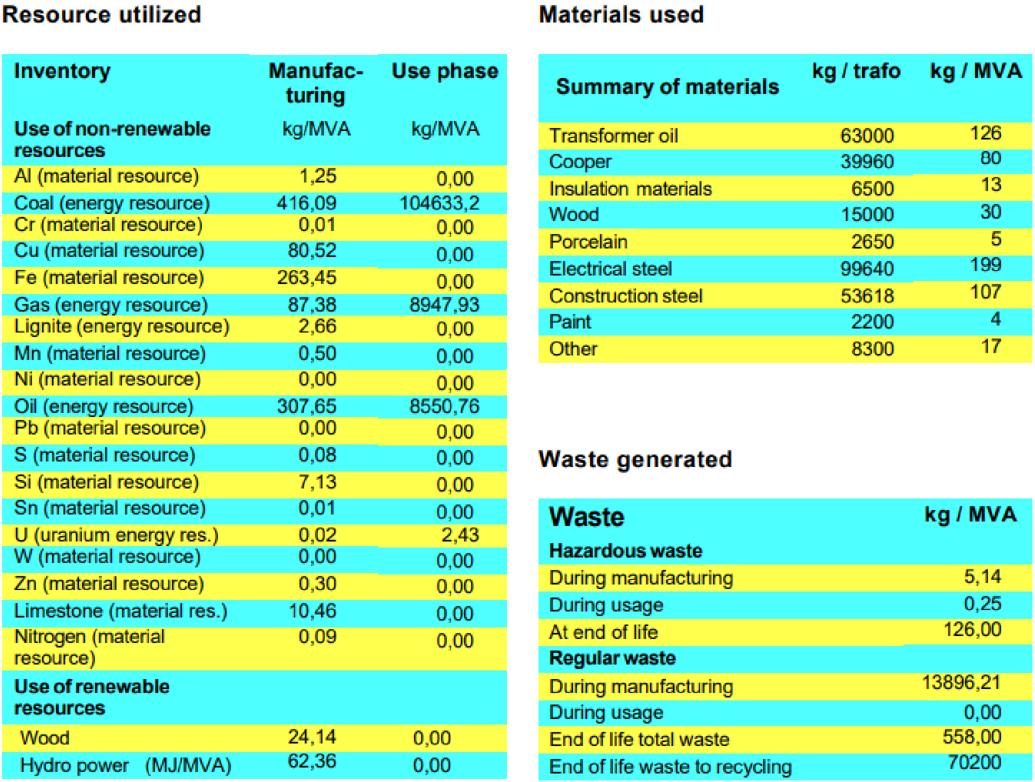
6.3.1.3 Mooring System

The mooring system only applies to FOWT and mooring chains and anchors were assumed to be the same model used in Hywind Scotland project due to the availability of the weight and material data of the mooring system of on the manufacturing factsheets of this project [81]. Weigh and material details of the mooring system are provided in the inventory list in Appendix F.

6.3.1.4 Power Transmission

Inter-array cables, export cables, and substation go into the power transmission category. For Hywind Tampen FOWF no substation was used since this farm supplies electricity to the nearby oil platforms, so no substation for FOWF base case was modelled in this study. Hywind Tampen inter-array and export cables were manufactured by JDR company [82] the same company that manufactured cables for Hywind Scotland FOWF, so for obtaining data on cables specification this study referred to the manufacturing factsheets [81] of Hywind Scotland project .For simplicity Dogger Bank C BFOWF cables were also assumed to be manufactured by JDR company in UK. The Hywind Tampen Inter array cables are 2.5 km long 66kV dynamic array cables [82] while in Dogger Bank C BFOWF static inter array cables with 250 km length were used [77]. Export cables of both base case projects were assumed to have the same material and cable specifications, based on the distance between Hywind Tampen farm and each of the five nearby platforms the export cable length is 45.4 km [82], and the length of Dogger Bank export cables were assumed to be equal to 130 km distance from the port [67]. Detailed information on cable materials, processes and used flows in ecoinvent database are given in the inventory list in Appendix F.

The Dogger Bank BFOWF substation is manufactured by Hitachi ABB Power Grid's (HAPG) and Aibel in Norway [83]. There was no data available for this substation. Nevertheless, as the capacity of Dogger bank project is 1.2 GW [84] it is assumed that a 1.2 GVA (=1200 MVA) capacity substation is used for this BFOWF. According to ABB Power Transmission EPD [85], the amount of materials used in the substation is given based on the kg/MVA. Therefore, by multiplying these values by 1200 MVA the weight of each material used was calculated. Figure 6.6 shows a screenshot of the utilized resources, materials, and generated waste of ABB substation manufacturing EPD. Table 6.3Table 2.1 summarizes calculated materials and energy used for manufacturing ABB TrafoStar 1200 MVA and the inventory list in Appendix F provides comprehensive details regarding Dogger Bank C substation materials, processes, and utilized flows available in the ecoinvent database.



Resource utilized

Inventory	Manufac-turing	Use phase
Use of non-renewable resources	kg/MVA	kg/MVA
Al (material resource)	1,25	0,00
Coal (energy resource)	416,09	104633,2
Cr (material resource)	0,01	0,00
Cu (material resource)	80,52	0,00
Fe (material resource)	263,45	0,00
Gas (energy resource)	87,38	8947,93
Lignite (energy resource)	2,66	0,00
Mn (material resource)	0,50	0,00
Ni (material resource)	0,00	0,00
Oil (energy resource)	307,65	8550,76
Pb (material resource)	0,00	0,00
S (material resource)	0,08	0,00
Si (material resource)	7,13	0,00
Sn (material resource)	0,01	0,00
U (uranium energy res.)	0,02	2,43
W (material resource)	0,00	0,00
Zn (material resource)	0,30	0,00
Limestone (material res.)	10,46	0,00
Nitrogen (material resource)	0,09	0,00
Use of renewable resources		
Wood	24,14	0,00
Hydro power (MJ/MVA)	62,36	0,00

Materials used

Summary of materials	kg / trafo	kg / MVA
Transformer oil	63000	126
Cooper	39960	80
Insulation materials	6500	13
Wood	15000	30
Porcelain	2650	5
Electrical steel	99640	199
Construction steel	53618	107
Paint	2200	4
Other	8300	17

Waste generated

Waste	kg / MVA
Hazardous waste	
During manufacturing	5,14
During usage	0,25
At end of life	126,00
Regular waste	
During manufacturing	13896,21
During usage	0,00
End of life total waste	558,00
End of life waste to recycling	70200

Figure 6.6 Utilized resources, materials, and generated waste for ABB substation manufacturing [85].

Table 6.3 Calculated materials and energy used for manufacturing ABB TrafoStar 1200 MVA [85].

Manufacturing materials and energy Per Transformer		Material and Energy Used
Materials	Transformer oil (ton)	151.2
	Copper (ton)	96
	Insulation materials (ton)	15.6
	Wood (ton)	36
	Porcelain (ton)	6
	Electrical steel (ton)	238.8
	Construction steel (ton)	128.4
	Paint (ton)	4.8
	Other (ton)	20.4
Energy	Electrical energy (KWh)	1800000
	Heat energy (KWh)	720000

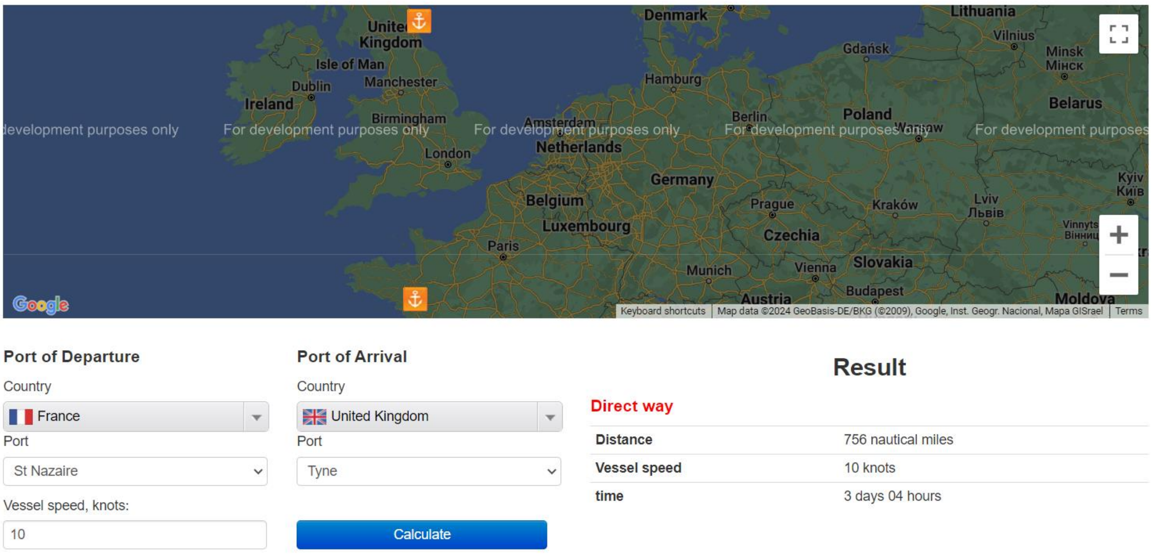
6.3.2 Transportation

In the selected boundaries for this study, two types of transport are covered. Firstly, transporting raw materials to the factories, as previously stated, this study employs market datasets from the ecoinvent database to model the raw material supply chain, encompassing both material acquisition and their transportation to Europe [33]. Secondly, transportation from factories to the installation port. These transports are done either by lorry or vessels. All assumptions and simplifications will be explained accordingly. Transportation of the two selected base case projects will be described in two separate sections.

6.3.2.1 Dogger Bank C BFOWF Transportation

The Haliade X 14 MW WT (RNA and tower) are manufactured in GE factory in Saint-Nazaire, France [86]. These WTs are shipped from this port in France to Tyne port in the UK where they are prepared to be installed in the BFOWF site.

The sea distance was calculated based on the sea-distances.org database which provides information about distances between ports around the world. [87].According to this database, the sea voyage distance between Saint-Nazaire and Tyne port is 756 nautical miles which by multiplying by 1.852 can be converted to km. The weight of 87 RNA and towers was calculated and multiplied by the distance in km, the resulting value in unit of tkm was used in ecoinvent coefficient for “transport, freight, sea, bulk carrier for dry goods”. Previous studies like [8] and [41] use “transport, freight, sea, ferry - GLO” , however, using a ferry could not be realistic due to the gigantic dimensions of WT components. The paper [33] by Brussa et al. uses the same ecoinvent coefficient for sea transport as this paper.



Port of Departure

Country: France

Port: St Nazaire

Vessel speed, knots: 10

Port of Arrival

Country: United Kingdom

Port: Tyne

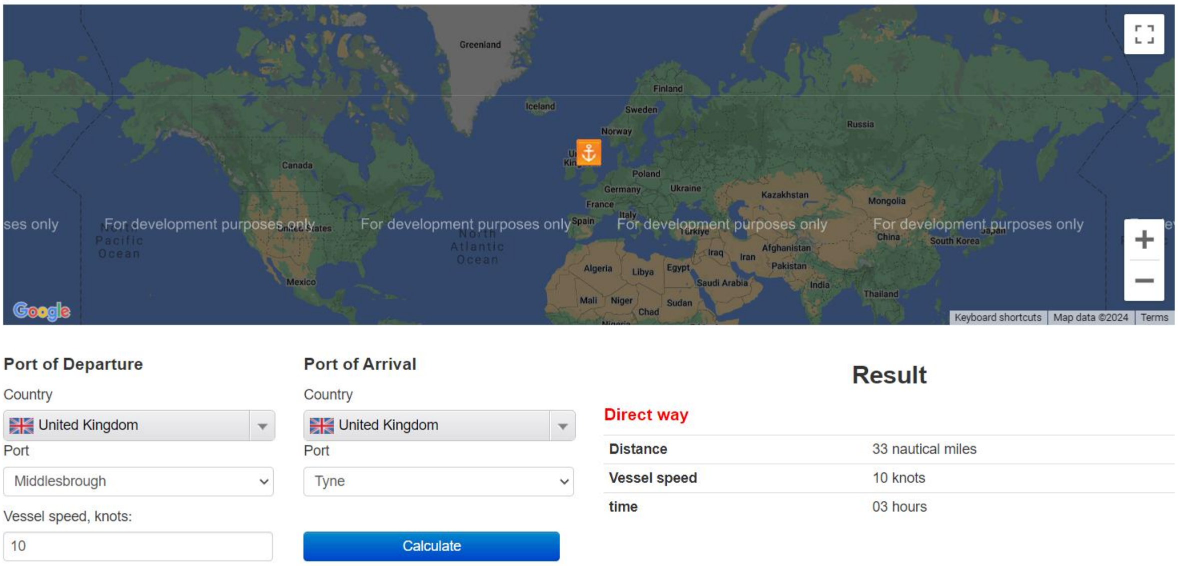
Result

Direct way

Distance	756 nautical miles
Vessel speed	10 knots
time	3 days 04 hours

Figure 6.7 Sea distance between GE WT factory in Saint-Nazaire and Tyne port in UK [87].

As described earlier Dogger Bank BFOWF cables manufacturer was assumed to be JDR company in the UK, the distance between Hartlepool, Victoria Dock near Middlesbrough port where cables are produced [88] and Tyne port was calculated using sea distance database and then multiplied by the weight of the cables, this value was used in ecoinvent coefficient for “transport, freight, sea, bulk carrier for dry goods”.



Port of Departure

Country: United Kingdom

Port: Middlesbrough

Vessel speed, knots: 10

Port of Arrival

Country: United Kingdom

Port: Tyne

Result

Direct way

Distance	33 nautical miles
Vessel speed	10 knots
time	03 hours

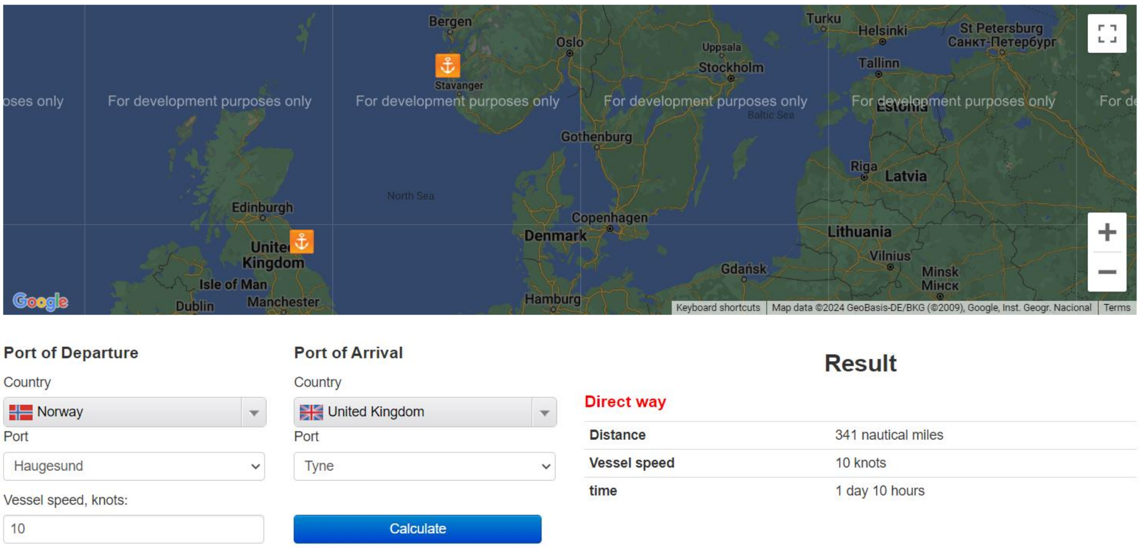
Figure 6.8 Sea distance between JDR cable factory in Middlesbrough and Tyne port in UK [61]

The same as the two earlier mentioned transportation methods was used to transport the substation built by Aibel company in Haugesund, Norway to Tyne in UK.

Dogger Bank C BFOWF transportation summary is given in Table 6.4.

Table 6.4 Dogger Bank C BFOWF transportation summary

Component	Vehicle	Freights (t)	Distance (km)	tkm
RNA and tower	Ship	6897.6	1400	9656645
Cables	Ship	3482.8	61	212450.8
Substation	Ship	697.2	632	440630



Port of Departure

Country: Norway

Port: Haugesund

Vessel speed, knots: 10

Port of Arrival

Country: United Kingdom

Port: Tyne

Result

Direct way

Distance	341 nautical miles
Vessel speed	10 knots
time	1 day 10 hours

Figure 6.9 Sea distance between Aibel substation factory in Haugesund, Norway and Tyne port in UK [87].

Transporting Substructures are assumed to be manufacture near Tyne port, and due to little impact, this transportation was not taken into account.

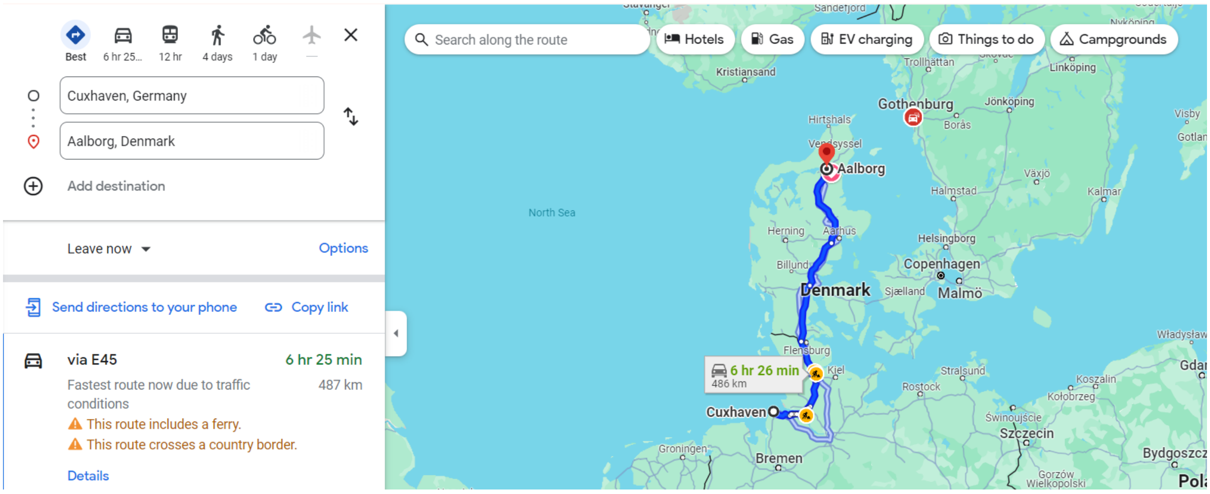
6.3.2.2 Hywind Tampen FOWF Transportation

According to some of Siemens Gamesa WT EPDs [89] this company's WT components are produced in locations describe in Table 6.5.

Table 6.5 Siemens Gamesa WT production locations [89].

Activity	Location	Owner
Backend & hub & generator manufacturing	Cuxhaven - Germany	SIEMENS GAMESA
Blades manufacturing	Aalborg - Denmark	SIEMENS GAMESA
Tower manufacturing	Give - DENMARK	WELCON

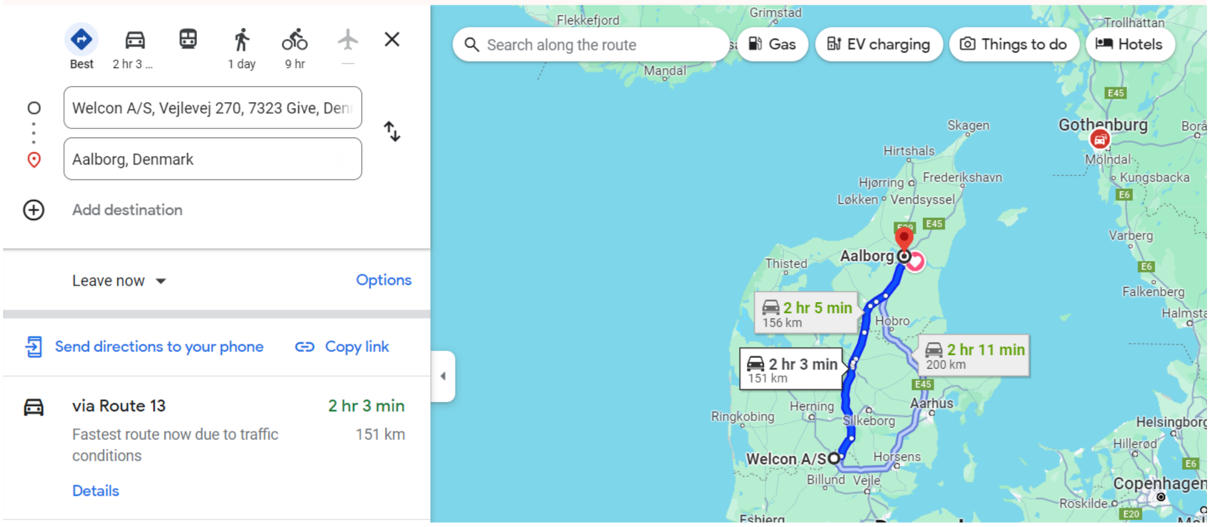
It is assumed that hub & generator manufactured in Cuxhaven – Germany was transported via lorry to Aalborg Denmark and together with other WT components were shipped to Gulen Norway, where Hywind Tampen WT is installed and towed to the wind farm site. The road distance between Cuxhaven and Aalborg was calculated 487 km using Google Maps. this value was multiplied by hub & generator weight and the resulting value in unit of tkm was used in the ecoinvent coefficient for "transport, freight, lorry >32 metric ton, EURO6".


Cuxhaven, Germany
Aalborg, Denmark

via E45 6 hr 25 min
Fastest route now due to traffic conditions 487 km
This route includes a ferry.
This route crosses a country border.

Figure 6.10 The distance between hub & generator factory in Cuxhaven, Germany and Aalborg Denmark [90].

With the same approach the distance between Welcon A/S company and Aalborg for transporting towers was calculated to be 151 km.



Welcon A/S, Vejlevej 270, 7323 Give, Den

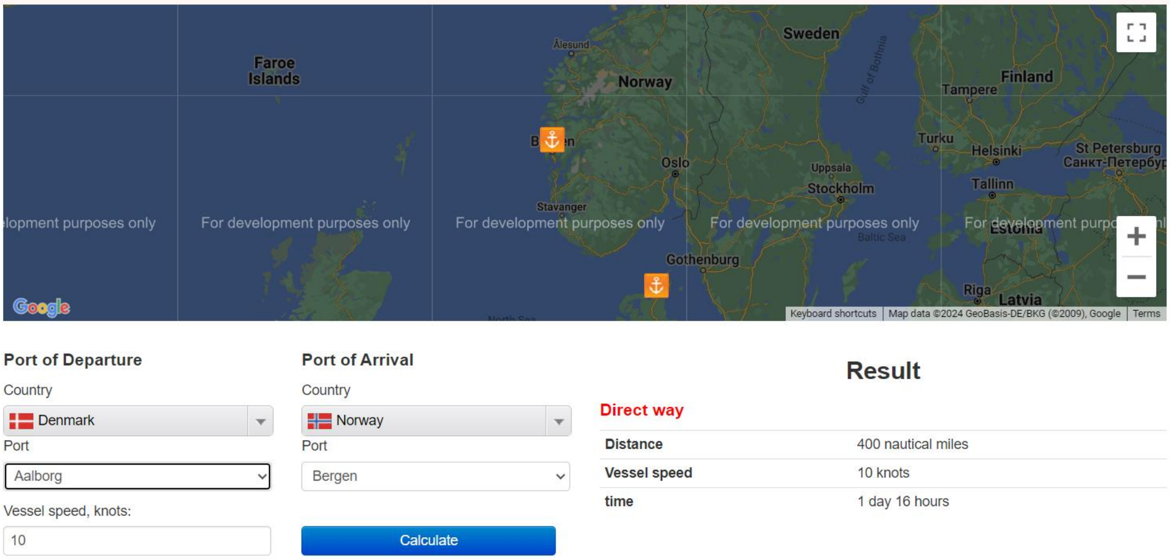
Aalborg, Denmark

via Route 13 2 hr 3 min

Fastest route now due to traffic conditions 151 km

Figure 6.11 The distance between tower factory in Give(Welcon factory), Denmark and Aalborg, Denmark [90].

RNA and towers transported via ship to Bergen port in Norway. The sea distance was calculated by using sea distance data base and then multiplied by weight of the 11 RNA and towers. This value was used in ecoinvent coefficient for “transport, freight, sea, bulk carrier for dry goods”.



Port of Departure

Country: Denmark

Port: Aalborg

Vessel speed, knots: 10

Port of Arrival

Country: Norway

Port: Bergen

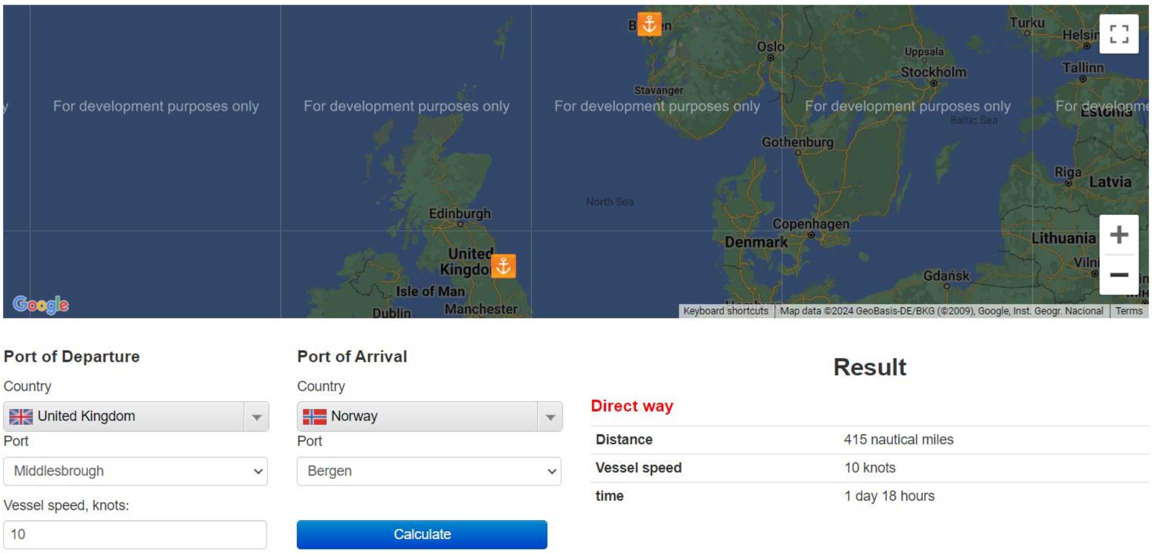
Result

Direct way

Distance	400 nautical miles
Vessel speed	10 knots
time	1 day 16 hours

Figure 6.12 Sea distance between Aalborg, Denmark and Bergen port in Norway [87].

The same approach applied to cables that were manufactured by JDR company in UK and transported via ship to Bergen. The distance was calculated 415 nautical miles (=769 km).



Port of Departure

Country: United Kingdom

Port: Middlesbrough

Vessel speed, knots: 10

Port of Arrival

Country: Norway

Port: Bergen

Result

Direct way

Distance	415 nautical miles
Vessel speed	10 knots
time	1 day 18 hours

Figure 6.13 Sea distance between JDR cable factory in Middlesbrough and Bergen port in Norway [87].

The foundation of the Hywind Tampen project was made in the installation port, also mooring and chain transport were assumed to be manufactured at the Hywind Tampen installation port and no transportation was calculated for these components. The Hywind Tampen FOWF transportation summary is given in Table 6.6.

Table 6.6 Hywind Tampen FOWF transportation summary

Component	Vehicle	Freights (t)	Distance (km)	tkm
Backend & hubs	Truck	3,317.38	487	1,615,564
Towers	Truck	7,590	151	1,146,090
WTG	Ship	13,049.50	740	9,656,645
Cables	Ship	442.95	769	340,627

6.3.3 Installation

Partial information on the vessels employed for the Dogger Bank and Hywind Tampen projects was accessible. Whenever feasible, this data was utilized in calculations, however, when no data on vessels' fuel consumption, energy demand, and speed were not available, the available data of similar vessels obtained from [1] study. Most previous studies used "transport, freight, sea, ferry - GLO" process in ecoinvent to model the emission from installation activities of vessels, however, this study opted for ecoinvent's "diesel, burned in diesel-electric generating set" process [1]. It is important to mention that in this study wait on weather conditions (WOW) such as high winds, high waves, poor visibility, etc. is neglected for installation and other offshore activities. The vessels' travel speeds were obtained from Ship Atlas [66]. Detailed installation calculation data are available in Appendix F.

6.3.3.1 Dogger Bank C BFOWF Installation

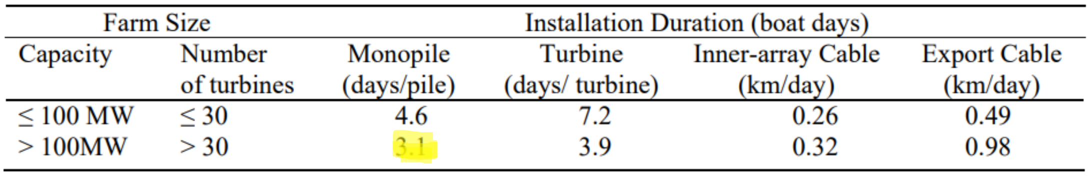
The installation of the Dogger Bank C project consists of 4 different stages: installing foundations, installing WTG, laying the cables, and finally installing the substation.

6.3.3.1.1 Monopile Foundation installation

The monopile foundations designed for the Dogger Bank project are among the largest ever used in offshore wind farms. The deployment of these foundations was the first operational usage of OHT's custom-built Heavy Lift Vessel (HLV), the Alfa Lift, which was developed exclusively for monopile installation [91].Due to accessibility to data, this study assumes a Self-Propelled Installation Vessel (SPIV) named MPI Resolution [1]. This vessel travel speed was obtained from Ship Atlas [92] to be 11 knots (=20.372 km/h). By dividing the distance between the port and the wind farm (130km) by the travel speed of the vessel, travel time was calculated to be 12.76 hours. Travel time was multiplied by two to calculate travel time to the farm site and back. This travel time then multiplied by MPI Resolution’s energy demand for travelling (4.3 MW) and the resulting value in MWh was used for ecoinvent’s “diesel, burned in diesel-electric generating set” process in openLCA® software.

The required time for installing foundations was assumed to be 3.1 days for each pile (including monopile and transition piece [93]), based on provided estimated time for various from sizes by [93]. The energy demand for installation was obtained by adding up energy demand for operation and energy demand for dynamic positioning (DP) [94] . DP systems are employed to maintain the position of marine vessels [95]. By multiplying energy demand for installing foundation and the installation time in hours, the energy used for installation operation was calculated. Then by adding up the energy used for travel and the energy used for installation operation total energy in MWh for installing each foundation was calculated.

Table 6.7 Estimated times required for installation from [93].



Farm Size		Installation Duration (boat days)			
Capacity	Number of turbines	Monopile (days/pile)	Turbine (days/ turbine)	Inner-array Cable (km/day)	Export Cable (km/day)
≤ 100 MW	≤ 30	4.6	7.2	0.26	0.49
> 100MW	> 30	3.1	3.9	0.32	0.98

Figure 6.14 Installing Dogger Bank project's foundations by a jack up SPIV [75].

6.3.3.1.2 WTG Installation

It is assumed that MPI Resolution vessel was used for WTG installation also as it is a Jack Up SPIV.As a result, travel time to the site and back and energy used for travelling was calculated the same as foundation travelling energy consumption.

Various times for 6 installation methods have been proposed by [93] book that can be seen in Figure 6.15 and Table 6.8.The assumed method for WTG was method 2, so the required time for installing WTGs was 1.8 days per wind turbine. The energy demand for installing WTG was obtained by adding up energy demand for operation and the energy demand for DP. By multiplying energy demand for installing WTG and the installation time in hours, the energy used for installation operation was calculated. Then by adding up the energy used for travel and the energy used for installation operation the total energy in MWh for installing each WTG was calculated.

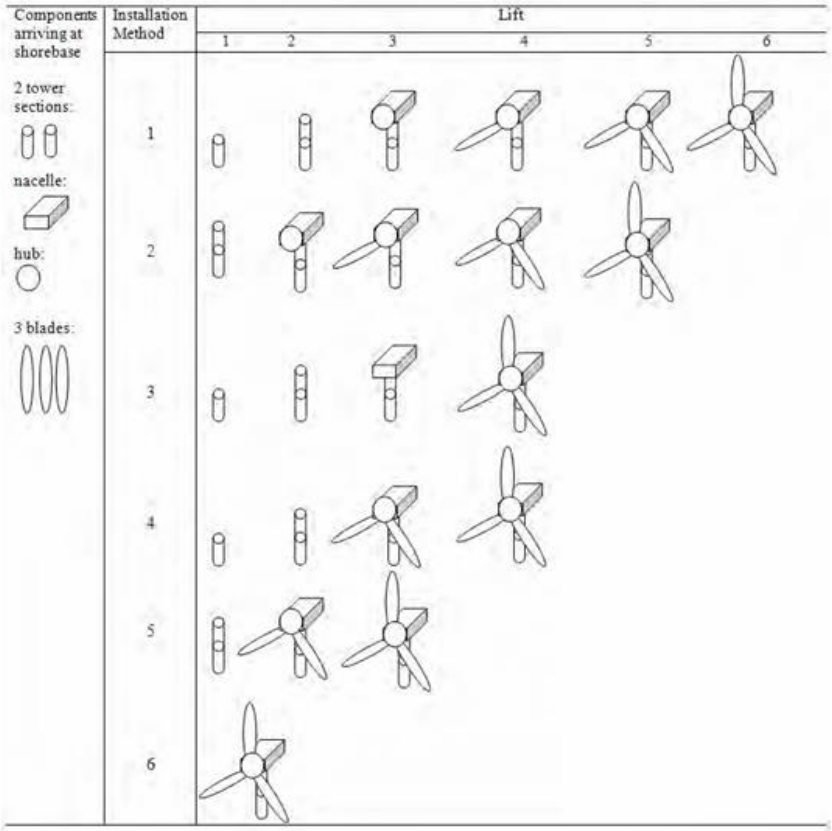


Figure 6.15 Diagram of various installation methods for WTG [93].

Table 6.8 Turbine installation rate based on different methods [93].

Installation method	Number of observations	Average rate (SD) (days/foundation)
1	1	1.9
2	1	1.8
3	7	7.1 (8.4)
4	6	5.1 (2.2)
5	2	6.2 (4.7)
6	0	

Figure 6.16 illustrates a jack up SPIV vessel installing Dogger Bank wind turbines.

Figure 6.16 A jack up SPIV vessel installing Dogger Bank wind turbines [96].

6.3.3.1.3 Cable laying

The cable laying vessel (CLV) used for Dogger Bank C project is assumed to be Seven Sun vessel. The energy for travel was calculated using the approach for the two aforementioned installed parts. According to Table 6.9, the boat days for installing inter-array cables was 0.32 km per day and 0.98 km per day for export cables. The operation time for laying both inter-array export cables was calculated as a total of 914 boat days. In total 206301 MWh energy was used to install cables for the FOWF.

Table 6.9 Cable installation durations for different farm sizes [93].

Farm Size		Installation Duration (boat days)			
Capacity	Number of turbines	Monopile (days/pile)	Turbine (days/ turbine)	Inner-array Cable (km/day)	Export Cable (km/day)
≤ 100 MW	≤ 30	4.6	7.2	0.26	0.49
> 100MW	> 30	3.1	3.9	0.32	0.98

6.3.3.1.4 Substation

It is assumed that the Dogger Bank substation foundation is monopile and based on provided information about installation durations of different wind farm components by [93] a 4-day installation duration assumption was made. The installation vessel was assumed to be MPI Resolution and with the same method as WTG the total installation energy demand was calculated.

6.3.3.2 Hywind Tampen FOWF installation

For installing FOWTs a completely different method compared BFOWTs installation is applied. The installation of the Hywind Tampen project consists of 2 stages: installing WTG and laying the cables. As mentioned earlier, this wind farm does not have a substation.

6.3.3.2.1 WTG

Firstly, by using Mammoet's PTC200-DS ring crane tower segments were assembled with spar concrete foundations that were already put in the deep port water. After assembling the tower, RNAs were installed over each tower using the same ring crane (method 1 in Figure 6.15) [97].

Jan Arne Wold/Woldcam/Equinor

Figure 6.17 Assembling Hywind Tampen wind turbine components at Gulen port, Norway [97].

After final assembly at port, the Hywind Tampen FOWTs were towed to their designated site by using three Anchor Handling Tug Supply (AHTS) vessels, one powerful AHTS vessel took the lead towing position, while the remaining two provided crucial support from behind ensuring stability and precise control during the transportation process. After reaching the wind farm site the leading AHTS kept the FOWT in place and ready for attachment to the mooring lines. Initially, the AHTS retrieved the pre-installed mooring lines, as shown in Figure 6.18. The wind turbine's chain was then attached to the mooring line on the AHTS deck. Work wires were employed to lift the mooring line from the seabed onto the AHTS [98]. According to [93] operation time at the site was 1.4 days per turbine (method 6 in Figure 6.15). The energy used for the operation was calculated for each AHTS by multiplying 1.4 days to the energy demand for operation of each AHTS (Sea Tiger vessel in this study).

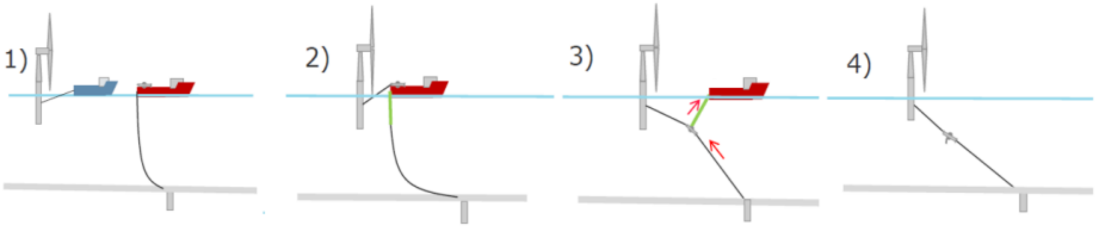


Figure 6.18 Hywind Tampen hook up operation [72].

The energy used for towing was obtained based on the towing speed of the Sea Tiger vessel. This time was multiplied with the towing energy demand of this vessel in MW, and the resulting value in MWh was multiplied by 3 to calculate the towing energy demand of the 3 AHTS. This number was added to the energy demand for travelling back to shore. The calculated energy used values were used for ecoinvent's "diesel, burned in diesel-electric generating set" process.

6.3.3.2.2 Cable laying

CLV used for the Dogger Bank C project is assumed to be the Seven Sun vessel. According to Table 6.9 the boat days for installing inter-array cables was 0.26 km per day and 0.49 km per day for export cables. The operation time for laying both inter-array and export cables for the FOWF was calculated a total of 130 boat days. In total 29,439 MWh energy was used to install cables for the Hywind Tampen FOWF.

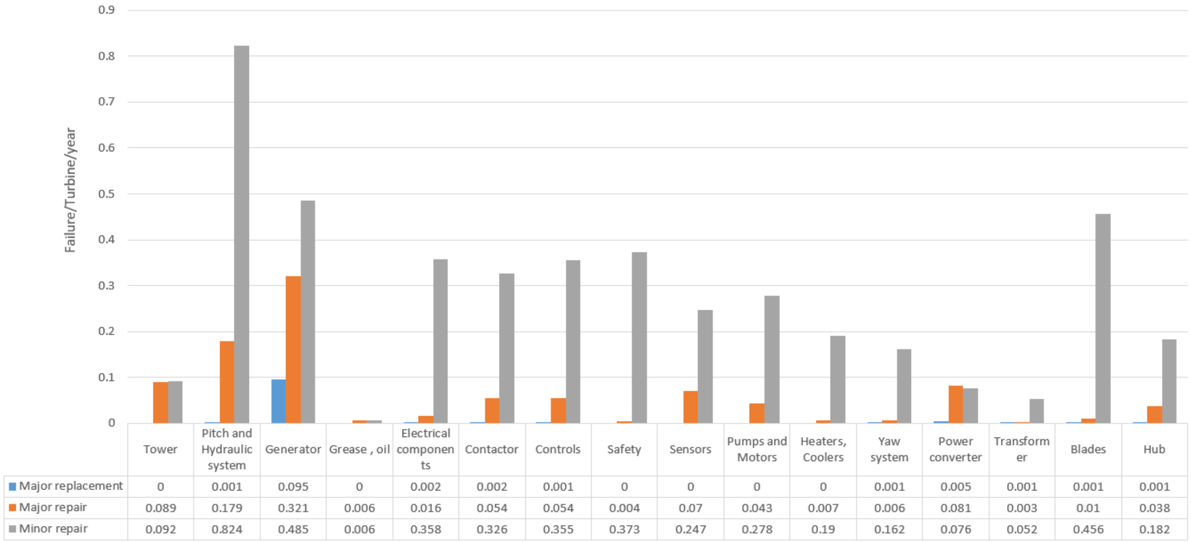
6.3.4 Operation and Maintenance (O&M)

This stage quantifies emission from operations and maintenance (O&M) activities that consist of unexpected maintenance due to failures, regular preventative maintenance, and spare parts. It was worth mentioning that as there is no data on ecoinvent database for Remotely Operated Vehicle (ROV) their activities and emissions were neglected in this study. Moreover, for simplicity WOW conditions are not taken into account for O & M activities. Detailed O&M calculation data are available in Appendix F.

6.3.4.1 Hywind Tampen FOWF O&M

6.3.4.1.1 Unexpected Maintenance

Offshore wind failure rates are scarcely documented in the literature. The assumed failure rates for FOWF in this study were based on [99] which is a thorough study on 350 OWTs throughout Europe. Figure 6.19 illustrates the annual failure rates of FOWT components which are categorized into Major replacement, Major repair, and Minor repair.



	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

Figure 6.19 Annual failure rates of FOWT components [99].

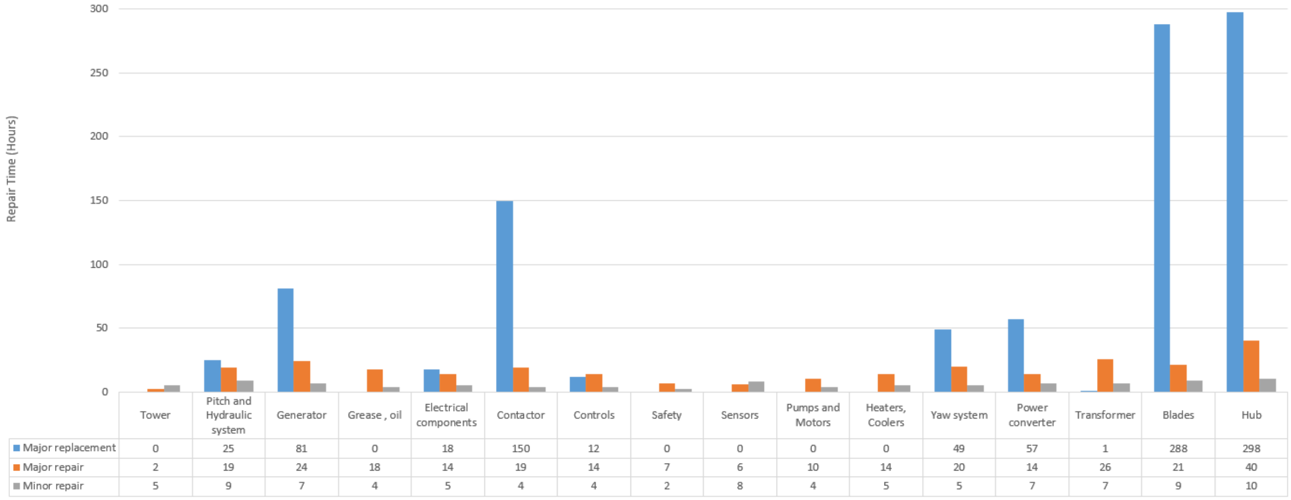
Failure rates of mooring chains , anchors and cables were obtained from [100] and were assumed to be according to Table 6.10.

Table 6.10 Failure rates of mooring , anchors and cables [100].

Component	Failure/Turbine/Year	O & M category
Mooring chains	0.14892	Major replacement
Anchors	0.15768	Major replacement
Cables	0.167	Major replacement

To get a total number of failures of each turbine during its lifetime, the mentioned annual failure rates were multiplied by the number of turbines of the farm and lifetime (×11×20).

The time required for repairing each component within each O &M category were obtained from [100], and has been illustrated in Figure 6.20.



	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	25	81	0	18	150	12	0	0	0	0	49	57	1	288	298
🟧 Major repair	2	19	24	18	14	19	14	7	6	10	14	20	14	26	21	40
▨ Minor repair	5	9	7	4	5	4	4	2	8	4	5	5	7	7	9	10

Figure 6.20 The time required for repairing each component within each O &M category [100].

The time required for repairing each failure of mooring chains, anchors and cables was obtained from [100] and was assumed to be according to Table 6.11.

Table 6.11 Time required for repairing each failure of mooring chains , anchors and cables [100].

Component	Repair Time (Hours)	O & M category
Mooring chains	12	Major replacement
Anchors	12	Major replacement
Cables	24	Major replacement

It is assumed that 2 types of vessels were used for O&M activities, for pitch, hydraulic system, blades, and generator which are large components, SPIV was used and Offshore Support Vessel (OSV) was utilized for other smaller components. It was assumed that SPIV was MPI Resolution and OSV was Dina Star vessel. With available energy demand data for these vessels, energy used for travelling to the site and O&M operation based on repair hours for each component was calculated in MWh. With the same approach as the installation phase these values were used for ecoinvent’s “diesel, burned in diesel-electric generating set” process in openLCA® software.

Table 6.12 Vessels used for repairing each component.

Component	Vessel Type	Vessel Name
Pitch, hydraulic system, blades, and generator	SPIV	MPI Resolution
Other components	OSV	Dina Star

6.3.4.1.2 Regular Maintenance

Based on Hywind Scotland’s Pilot Park Environmental Statement [75] which is a similar project to the Hywind Tampen project the WTG units are anticipated to undergo once-a-year preventative maintenance (PM). For regular PM of WTG, it is assumed a helicopter for transporting personnel and an OSV for transporting equipment is used which is a quite common method for OWT O&M operations [43]. It is estimated that the helicopter requires a total of 2 hours for round-trip travel to the site, while the operation of each turbine is expected to take 3 hours, resulting in a total of 5 hours per turbine.

The OSV visiting WTG was assumed to spend 3 hours of visiting for each turbine, resulting in 33 hours annually for the 11 turbines of the farm.

Another OSV has been assumed for visiting mooring and anchors. It is also assumed 3 hours visit per turbine.

A small CLV named Giulio Verne was used for checking subsea cables, assuming 1 km of a cable per hour is inspected [41].

The energy and emission calculations for OSV and CLV vessels followed the same method for installation phase vessels.

6.3.4.1.3 Spare Parts

With growing size of wind farms, the requirement for easily accessible key spare parts for quick replacement has become critical, particularly offshore where repair windows are restricted due to weather and logistical constraints. Spare parts are classified into two types: major spares, which have long manufacturing lead times and are held based on maintenance and asset management strategies, such as blades, gearbox parts, and generator control modules; and consumable spares, which are frequently used and can be controlled as consignment stock, such as lamps, lubricants, and filters [43]. Current research suggests focusing on major spare parts and consumable spare parts are not taken into consideration.

As Arvesen et al. [101] found publicly available data on component exchange rates for wind turbines is limited. The German '250 MW Wind' monitoring program (WMEP) appears to be the sole source of such comprehensive data for a wind turbine fleet. This study adopts the rates proposed by [75], derived from a decade of real-world data collected through the WMEP program, which involved the analysis of data from 538 wind turbines. The annual replacement rate for large components is presumed to be 0.075 per wind turbine. For blades and generators, a rate 0.333 has been assumed. By multiplying these rates by the number of wind turbines and lifetime of the farm lifetime replacement rate per wind farm was calculated as shown in Table 6.13.

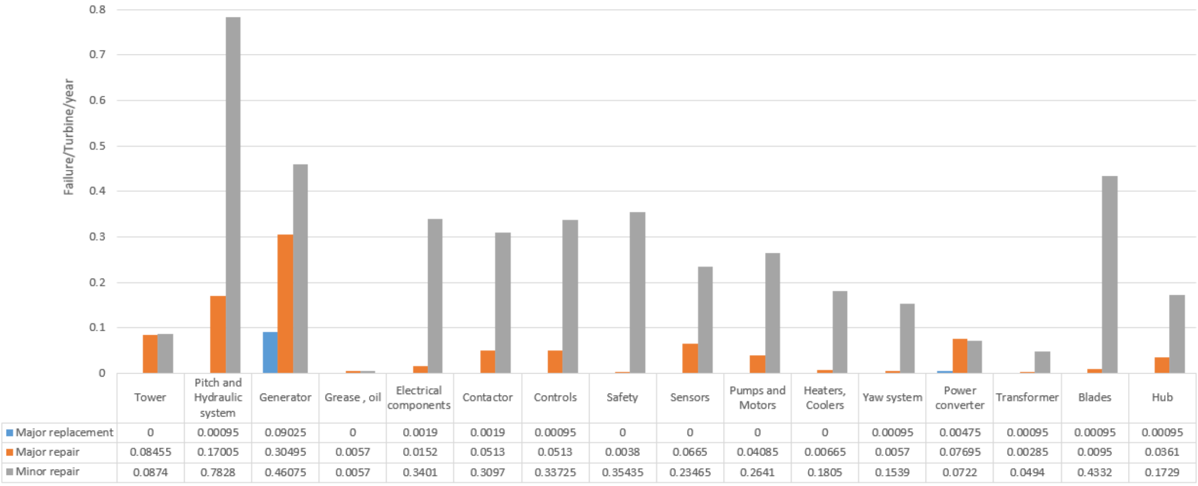
Table 6.13 Spare Parts replacement rates of Hywind Tampen project [101].

Spare Parts	**Annual replacement Per Wind Turbine**	**Annual replacement Per Wind Farm**	**Lifetime replacement Per Wind Farm**
Replacement large parts (Turret / Nose, Bedplate, Flange, Shaft Bearings, Yaw System)	0.075	0.825	16.5
Blades	0.333	3.667	73.3
Generators	0.333	3.667	73.3

6.3.4.2 Dogger Bank BFOWF O&M

6.3.4.2.1 Unexpected Maintenance

As previously stated, offshore wind failure rates are scarcely documented in the literature and there was not any publicly available data on failure rates of BFOWF. However, as [102] suggests FOWTs O&M is more expensive than BFOWTs due to harsh weather conditions further offshore, limited weather windows, and more complexity of floating technology. Moreover, [103] suggests that share of O&M in total Levelized Cost of Energy (LCOE) for FOWTs is 5 % more than BFOWTs. Based on this knowledge, this study assumes that annual failure rates and spare parts exchange rates of the Dogger Bank project are 5 % less than the Hywind Tampen project. The failure rate of cable was assumed to be 5 % less than Hywind Tampen's 0.167 failure/turbine/year.



	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	0.00095	0.09025	0	0.0019	0.0019	0.00095	0	0	0	0	0.00095	0.00475	0.00095	0.00095	0.00095
■ Major repair	0.08455	0.17005	0.30495	0.0057	0.0152	0.0513	0.0513	0.0038	0.0665	0.04085	0.00665	0.0057	0.07695	0.00285	0.0095	0.0361
■ Minor repair	0.0874	0.7828	0.46075	0.0057	0.3401	0.3097	0.33725	0.35435	0.23465	0.2641	0.1805	0.1539	0.0722	0.0494	0.4332	0.1729

Figure 6.21Annual failure rates of BFOWT components [99].

The repair duration for each failure at the Dogger Bank project was assumed to be equivalent to that of the Hywind Tampen project, and the same method for calculating used energy by vessels was followed.

6.3.4.2.2 Regular Maintenance

The same vessels and methods for the Hywind Tampen regular maintenance emissions calculations have been followed here. The only differences were that no mooring chain and anchors exist in the Dogger Bank project as it is BFOWF, and this project had a substation. For substation an annual visit by SPIV (MPI Resolution) has been assumed with 8 hours on site for each visit.

6.3.4.2.3 Spare Parts

As previously stated, spare parts replacement rates for the Dogger Bank project were assumed to be 5 % less than each replacement rate of the Hywind Tampen project. These replacement rates can be seen in Table 6.14

Table 6.14 Spare Parts replacement rates of Dogger Bank project [101].

Spare Parts	Annual replacement Per Wind Turbine	Annual replacement Per Wind Farm	Lifetime replacement Per Wind Farm
Replacement large parts (Turret / Nose, Bedplate, Flange, Shaft Bearings, Yaw System)	0.0713	6.199	124
Blades	0.317	28	551.6
Generators	0.317	28	551.6

6.3.5 Decommissioning

Disassembling or decommissioning individual wind turbines within an offshore wind farm is largely the opposite of the installation procedure [1]. This study adopts the methodology of some previous research [41], [8], [40] that assume emissions from decommissioning are the reverse and equivalent to the installation stage.

6.4 Electricity Production of The Wind Farms

Annual electricity production of each turbine was calculated using Equation (6.2).

$$E_{T,A} = C \times C_F \times t_A \tag{6.2}$$

Where $E_{T,A}$ is Annual electricity production of each turbine (MWh), C is capacity of each turbine (MW), C_F is capacity factor[5] and t_A is number of hours in one year. For example, E_T for 14 MW BFWT would be:

$$E_{T,A} = 14 \times 0.453 \times 24 \times 365 = 55{,}556\ MWh$$

Lifetime electricity production of each turbine was calculated using Equation (6.3).

$$E_{T,L} = E_{TA} \times N_L \tag{6.3}$$

Where N_L is number of years that turbine works (Lifetime), so we have:

$$E_{T,L} = 55{,}556 \times 20 = 1{,}111{,}118 \text{ MWh}$$

Based on study [104] there is 0.4 % electrical loss in each 100 km export subsea cable, so the loss for 130 km distance to shore would be 0.52% and $E_{T,L}$ was calculated :

$$E_{T,L}\text{=1,111,118 (1-0.0052) =1,105,341 MWh}$$

Lifetime electricity production of the farm was calculated using Equation (6.4).

$$E_{F,L} = E_{T,L} \times N_T \tag{6.4}$$

Where N_T is the number of turbines, for the Dogger Bank farm:

$$E_{F,L} = 1{,}105{,}341 \times 87 = 96{,}164{,}631 \text{ MWh}$$

Total downtime (repair hours) due to failures were calculated to be 86,267 hours for the Dogger Bank farm. Electrical loss due to downtime was calculated using Equation (6.5).

$$E_{Loss} = C \times C_F \times t_F \tag{6.5}$$

---

[5] The capacity factor (CF) represents the ratio of the turbine's yearly electricity production to the maximum potential electricity it could generate in a year [41].

Where C is capacity of each turbine (MW), C_F is capacity factor and t_F is total downtime (repair hours) due to failures. In case of the Dogger Bank:

$$E_{Loss} = 14 \times 0.453 \times 86{,}267 = 547{,}105 \text{ MWh}$$

Then lifetime electrical power delivery of the farm after all losses (real power production), $E_{F,L,R}$ was calculated by Equation (6.6).

$$E_{F,L,R} = E_{F,L} - E_{Loss} \tag{6.6}$$

For the Dogger Bank wind farm:

$$E_{F,L,R} = 96{,}164{,}631 - 547{,}105 = 95{,}617{,}526 \text{ MWh}$$

By applying the same method $E_{F,L,R}$ for Hywind Tampen project was calculated 8,256,878 MWh. The detailed calculations could be found in Appendix F.

7 Results and Discussion

This chapter presents the results of the conducted LCA for the two base case scenarios along with some other scenarios for conducting sensitivity analysis. The results will be discussed, analyzed, and compared to the literature. Finally, other environmental impacts of offshore windfarms on marine wildlife such as seabirds and marine mammals will be briefly discussed.

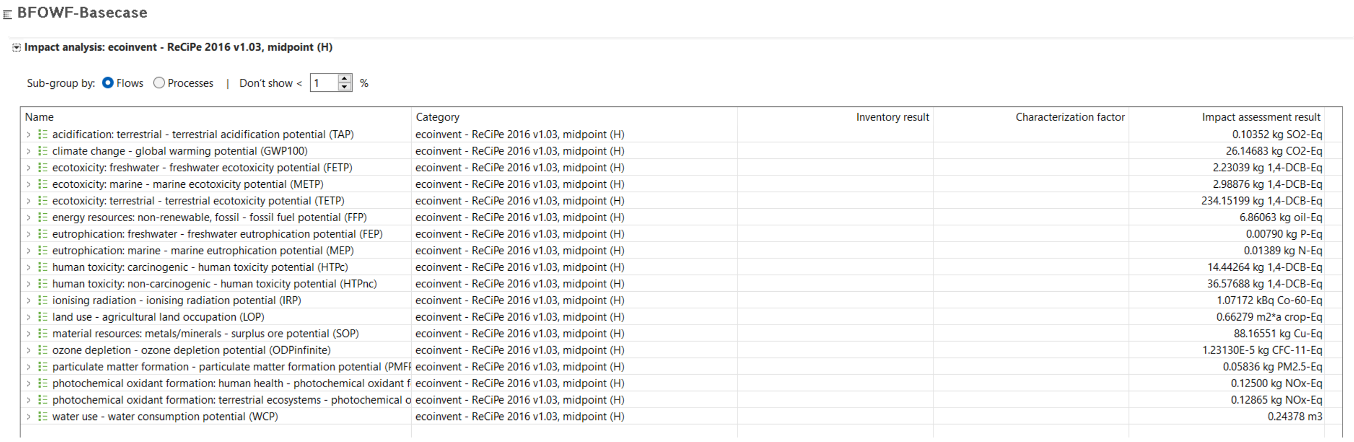
7.1 Base case Scenarios LCA Impacts

By applying the ReCiPe Midpoint (H) 2016 method 18 impact categories were measured for the two base case scenarios. As the defined functional unit in this study is 1 MWh of delivered electricity to the grid, these impact values are equal to the impact value divided by $E_{F,L,R}$ (the lifetime electrical power delivery of the farm after all losses in MWh) which was calculated using Equation (7.1). As an example, the global warming potential (GWP) is calculated according to Equation (7.1). This GWP value represents the greenhouse gas emissions released throughout the wind farm's life cycle to generate 1 MWh of electricity and subsequently feed it into the grid.

$$GWP(kg\ CO_2eq/\ MWh) = \frac{Life\ Cycle\ GHG\ Emissions\ (kg\ CO_2\ equivalent)}{Wind\ Farm\ Life\ Cycle\ Generation\ (MWh)} \tag{7.1}$$

7.1.1 Dogger Bank C BFOWF Impacts

The results from the openLCA® software, encompassing 18 impact categories for the Dogger Bank C BFOWF, have been illustrated in Figure 7.1


BFOWF-Basecase

Impact analysis: ecoinvent - ReCiPe 2016 v1.03, midpoint (H)

Sub-group by: ● Flows ○ Processes | Don't show < 1 %

Name	Category	Inventory result	Characterization factor	Impact assessment result
acidification: terrestrial - terrestrial acidification potential (TAP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			0.10352 kg SO2-Eq
climate change - global warming potential (GWP100)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			26.14683 kg CO2-Eq
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			2.23039 kg 1,4-DCB-Eq
ecotoxicity: marine - marine ecotoxicity potential (METP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			2.98876 kg 1,4-DCB-Eq
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			234.15199 kg 1,4-DCB-Eq
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			6.86063 kg oil-Eq
eutrophication: freshwater - freshwater eutrophication potential (FEP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			0.00790 kg P-Eq
eutrophication: marine - marine eutrophication potential (MEP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			0.01389 kg N-Eq
human toxicity: carcinogenic - human toxicity potential (HTPc)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			14.44264 kg 1,4-DCB-Eq
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			36.57688 kg 1,4-DCB-Eq
ionising radiation - ionising radiation potential (IRP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			1.07172 kBq Co-60-Eq
land use - agricultural land occupation (LOP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			0.66279 m2*a crop-Eq
material resources: metals/minerals - surplus ore potential (SOP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			88.16551 kg Cu-Eq
ozone depletion - ozone depletion potential (ODPinfinite)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			1.23130E-5 kg CFC-11-Eq
particulate matter formation - particulate matter formation potential (PMFI	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			0.05836 kg PM2.5-Eq
photochemical oxidant formation: human health - photochemical oxidant f	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			0.12500 kg NOx-Eq
photochemical oxidant formation: terrestrial ecosystems - photochemical o	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			0.12865 kg NOx-Eq
water use - water consumption potential (WCP)	ecoinvent - ReCiPe 2016 v1.03, midpoint (H)			0.24378 m3

Figure 7.1 The results from the openLCA® software, encompassing 18 impact categories for the Dogger Bank BFOWF.

As can be seen in Figure 7.1 the GWP for BFOWF is equal to 26.15 kg CO_2-Eq/ MWh which also can be defined as 26.15 g CO_2-Eq / KWh. The contribution of each stage of the life cycle stage of the Dogger Bank project to GWP was calculated using the openLCA® software and has been shown in Table 7.1.

Table 7.1 The contribution of each stage of the life cycle of the Dogger Bank project to GWP

Stage	Contribution (%)	GWP (kg CO_2-Eq / MWh)
Wind Turbine Manufacturing	43.84%	11.46
Substructure Manufacturing	11.84%	3.10
Power Transmission Manufacturing	1.36%	0.36
Transportation	0.13%	0.03
Installation	4.44%	1.16
O & M vessel	14.60%	3.82
O & M spare parts	19.35%	5.06
Decommissioning	4.44%	1.16

7.1.2 Hywind Tampen FOWF Impacts

The GWP for FOWF is equal to 36.78 kg CO_2-Eq/ MWh which also equals 36.78 g CO_2-Eq / KWh. The contribution of each stage of the life cycle of the Hywind Tampen project to GWP is described in Table 7.2.

Table 7.2 The contribution of each stage of the life cycle of the Hywind Tampen project to GWP

Stage	Contribution (%)	GWP (kg CO_2-Eq / MWh)
Wind Turbine Manufacturing	26.79%	9.85
Substructure Manufacturing	26.73%	9.83
Mooring System Manufacturing	2.84%	1.04
Power Transmission Manufacturing	1.32%	0.49
Transportation	0.05%	0.02
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

7.1.3 Comparing Bottom Fixed and Floating Base cases

The results of 18 impact categories of both base case scenarios are compared in Table 7.3.As can be seen, the GWP for the floating project is 36.78 kg CO_2-Eq/ MWh while for bottom fixed project this value is 26.15 kg CO_2-Eq/ MWh. For almost all impact categories, the value for the floating farm is higher than the bottom fixed farm.

Table 7.3 The results of 18 impact categories of both base case scenarios

Impact category	**Reference unit/MWh**	**Dogger Bank (Bottom Fixed)**	**Hywind Tampen (Floating)**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO_2-Eq	0.10	0.15
climate change - global warming potential (GWP100)	kg CO_2-Eq	26.15	36.78
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg1,4-DCB-Eq	2.23	2.93
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg1,4-DCB-Eq	2.99	3.90
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	234.15	305.75
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	6.86	8.75
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.01	0.01
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.01	0.01
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	14.44	15.89
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	36.58	46.71
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.07	1.01
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.66	0.72
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	88.17	71.09
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	0.00	0.00
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.06	0.08
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.12	0.21
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.13	0.21
water use - water consumption potential (WCP)	m3	0.24	0.23

Figure 7.2 compares the GWP of each stage of life cycle stages to the total GWP of the base case scenarios. As can be seen, the only stage that Dogger Bank had a higher GWP was the wind turbine manufacturing stage.

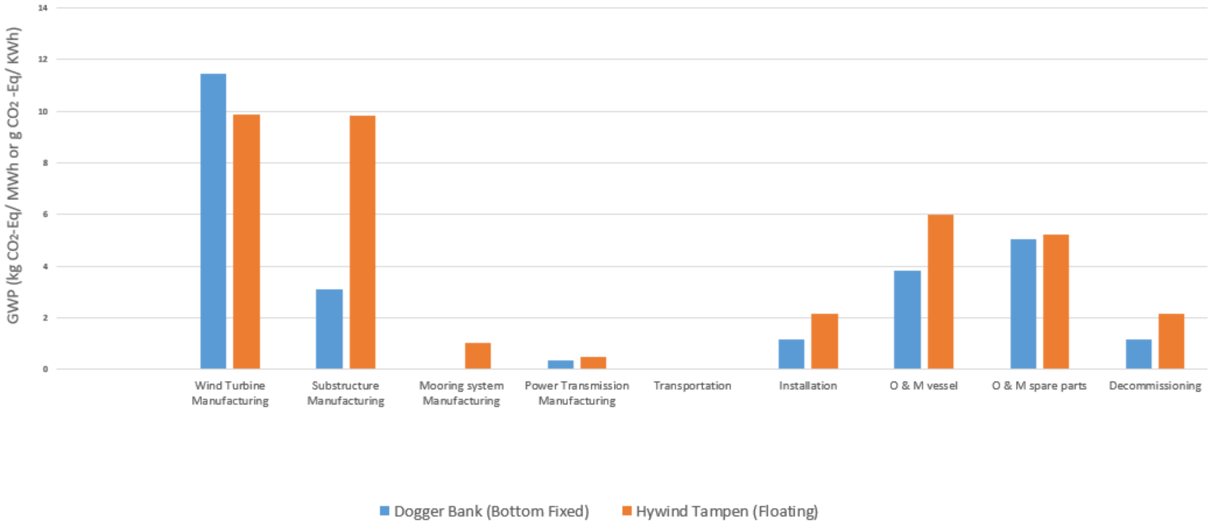


Figure 7.2 The GWP of each life cycle stages for base case scenarios.

The GWP of the wind turbine manufacturing stage for Dogger Bank was 11.46 kg CO_2-Eq/ MWh while for Hywind Tampen it was 9.85 kg CO_2-Eq/ MWh. However, to compare the GWP per MW of wind turbine capacity, $E_{F,L,R}$ was multiplied by GWP (Kg CO_2-Eq per MW) to compute GWP total in kilograms, then this number was divided by the lifetime of 20 years and the number of turbines in each farm to get the value of GWP per turbine per year (kg) finally this was divided by the capacity of each turbine. The resulting values are provided in Table 7.4 and when comparing these values (45 and 46.2 for BFOWF and FOWF respectively), they are quite close as the technology used for each turbine was the same.

Table 7.4 GWP per MW of capacity of wind turbines for wind turbine manufacturing stage.

Scenario	$E_{F,L,R}$ **(lifetime electrical power delivery of the farm after all losses) (MWh)**	**GWP (Kg CO_2-Eq per MWh)**	**GWP total (Kg)**	**GWP per turbine per year (kg)**	**GWP (tones CO_2-Eq per MW per year)**
BFOWF	95,617,526	11.46	1.09617E+9	6.30E+05	45.0
FOWF	8,256,878	9.85	8.14E+7	3.70E+05	46.2

Some heatmaps were generated using Microsoft Excel® oftware to assist in visualizing the results. These heatmaps use three colors to represent different impact levels. Green shades indicate lower impact values, yellow represents the 50th percentile (which is the midpoint), and red gets more intense as values go beyond the midpoint toward maximum impact. Figure 7.3 depicts the applied rule for generating heatmaps using Microsoft Excel®.

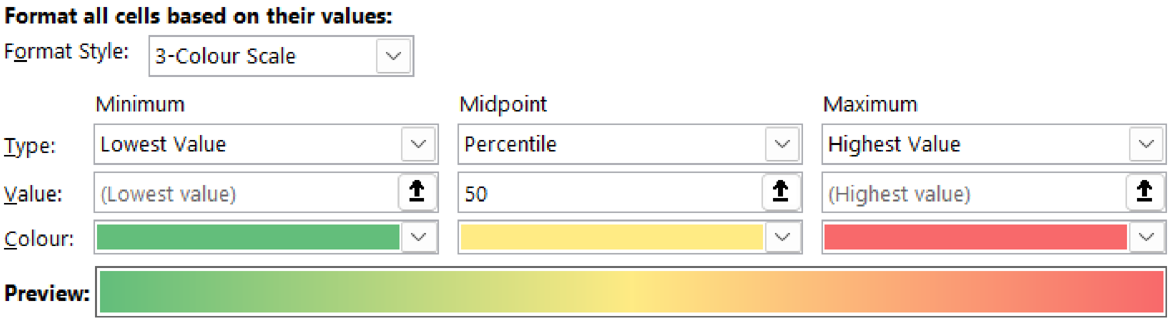


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Figure 7.3 The applied rule for generating heatmaps using Microsoft Excel®.

Table 7.5 shows the contributions of each life cycle stage to the total GWP in a heatmap.

Table 7.5 A heatmap of the contribution of each life cycle stage to the total GWP for base case scenarios

	Dogger Bank (Bottom Fixed)		**Hywind Tampen (Floating)**	
Stage	**Contribution (%)**	**GWP (kg CO2-Eq/ MWh[6])**	**Contribution (%)**	**GWP (kg CO2-Eq/ MWh)**
Wind Turbine Manufacturing	43.84%	11.46	26.79%	9.85
Substructure Manufacturing	11.84%	3.10	26.73%	9.83
Mooring system Manufacturing	-	-	2.82%	1.04
Power Transmission Manufacturing	1.36%	0.36	1.32%	0.49
Transportation	0.13%	0.03	0.07%	0.03
Installation	4.44%	1.16	5.91%	2.17
O & M vessel	14.60%	3.82	16.27%	5.98
O & M spare parts	19.35%	5.06	14.18%	5.22
Decommissioning	4.44%	1.16	5.91%	2.17
Total	100.00%	26.15	100.00%	36.78

As can be seen, the figures suggest that bottom-fixed wind farm has a lower GWP impact compared to floating wind farm across most life cycle stages (except transportation).

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[6] 1 MWh is the defined functional unit in this study, and the reported GWP value represents the greenhouse gas emissions released throughout the wind farm's life cycle to generate 1 MWh of electricity and subsequently feed it into the grid.

The share of transportation is very low in both scenarios, with 0.03 and 0.02 for Dogger Bank and Hywind Tampen respectively. In both scenarios, manufacturing has the highest contribution to the total GWP, the substructure of the floating farm had higher emissions due to using concrete for manufacturing the spar substructure.

The second and third contributors to the total GWP are O & M vessel and O & M spare parts respectively. The GWP of O&M in floating case is higher due to higher failure rates and using more spare parts. Also, the floating case is further offshore compared to the bottom fixed case. It is worth mentioning that, according to calculations of fuel consumption for vessels used for O&M, in both Dogger Bak and Hywind Tampen, 90 % of vessels' fuel consumption was due to failures that occurred and only 10% accounted for regular maintenance.

Installing floating turbines was more complex and required more time in offshore activities, as a result, the GWP in installation for floating is 1.01 kg higher. The GWP of installation and decommissioning are the same because this study assumed that emissions from decommissioning are the reverse and equivalent to the installation stage.

Manufacturing of power transmission in floating emits more, due to more complexity and type of materials used for dynamic inter-array subsea cables.

The contribution of the main five life cycle stages to total GWP for base case scenarios is compared in Figure 7.4. Although some stages show higher percentages in the BFOWF, the overall GWP amount is lower than that of the FOWF.

Figure 7.4 Contribution of the main five life cycle stages to total GWP for base case scenarios.

The specific environmental impact results are impacted by characteristics unique to each wind farm (e.g., turbine number, power rating, capacity factor, distance from the port). To partially lessen the impact of these factors the GWP per MW of wind turbine capacity, $E_{F,L,R}$ was multiplied by GWP (Kg CO_2-Eq per MW) to compute GWP total in kilograms, then this number was divided by the lifetime of 20 years, and the number of turbines in each farm to get the value of GWP per turbine per year (kg) finally this was divided by the capacity of each turbine. The resulting values are provided in Table 7.6. In this way the floating and bottom fixed technologies can be compared and in the bottom fixed scenario, the result was 102.6 tonnes CO_2-Eq per MW on an annual basis, while for the floating it was calculated to be 172.5.

One reason for this discrepancy could be the fact that bottom-fixed wind turbines' power rating was much larger than the floating wind turbines' power rating.

Table 7.6 GWP per MW of capacity of wind turbines for base case scenarios.

Scenario	$E_{F,L,R}$ **(lifetime electrical power delivery of the farm after all losses) (MWh)**	**GWP (Kg CO_2-Eq per MWh)**	**GWP total (Kg)**	**GWP per turbine per year (kg)**	**GWP (tones CO_2-Eq per MW per year)**
BFOWF	95,617,526	26.15	2.5004E+9	1.44E+06	102.6
FOWF	8,256,878	36.78	3.03688E+8	1.38E+06	172.5

7.2 Sensitivity Analysis

Sensitivity analysis determines the impact of an independent variable on a specific dependent variable under certain conditions [105]. This section investigates how changes in critical characteristics during the life cycle stages of an offshore wind farm affect the overall results of the life cycle assessment.

This study seeks to systematically vary these factors and analyze the resulting changes in environmental impact indicators to:

- Identify key elements affecting the environmental impact of offshore wind projects.
- Evaluate the validity of LCA findings and identify relevant areas for future research.
- Learn about potential opportunities for environmental optimization throughout the life cycle of offshore wind projects.

In the following sections, the sensitivity to capacity factor (CF), lifetime of the wind farm (LT), distance to the shore, and O&M strategies will be assessed. Additionally, in the following, the GWP is mainly compared and the values for the other 17 environmental impacts, along with heatmaps for each scenario, are provided separately in the Appendix C and E.

7.2.1 Capacity Factor (CF)

By changing the capacity factor, the electrical power delivery of the farm ($E_{F,L,R}$) changed, by applying these values in the openLCA® software model, the results changed accordingly. The sensitivity analysis was done for two different CFs, CF=40% and CF=60%

7.2.1.1 CF=40%

Both base case scenarios had bigger CF than 40 %, by decreasing CF it was expected that GWP and other environmental impacts see an increase and the results met this expectation. No change in the percentage of contribution of each life cycle stage occurred, but only the amount of GWP for each stage saw an increase.

7.2.1.2 CF=60%

Both base case scenarios had lower CF than 60 %, by increasing CF it was expected that GWP and other environmental impacts decline, and the results confirmed this expectation.

Both CF scenarios are compared with the base cases in Figure 7.5. Increasing CF would lead to significant decrease in GWP amount and vice versa.

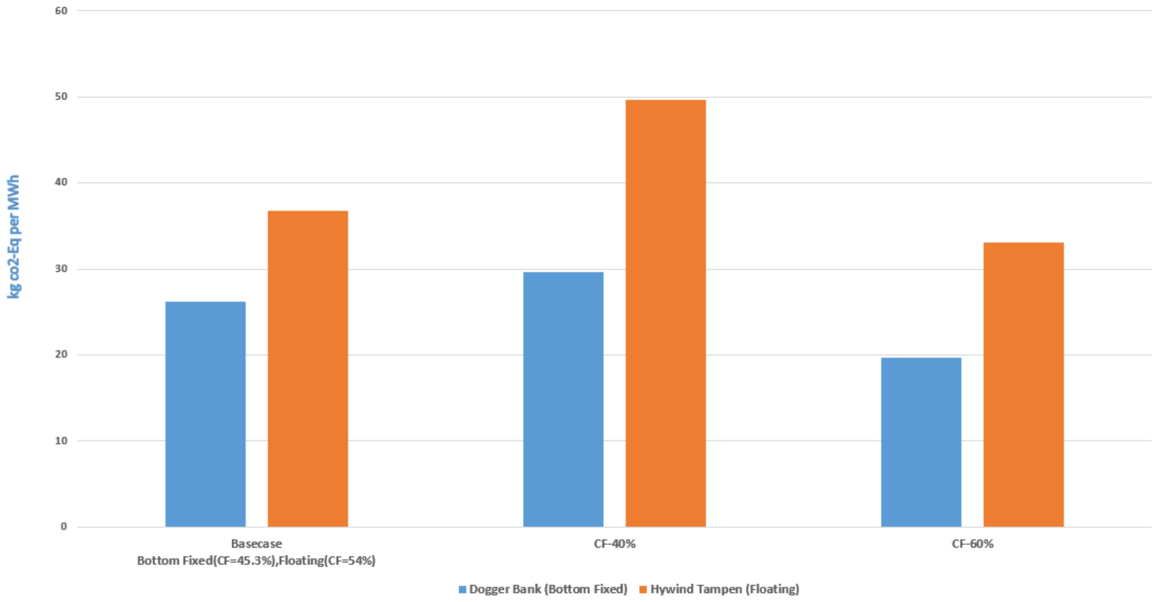

Figure 7.5 Comparing the two scenarios for CF with the base cases.

In the base case scenarios, the capacity factor (CF) of the floating project was higher than that of the bottom-fixed project. However, during sensitivity analysis, equal CFs were assumed for both wind farms, leading to a further widening of the difference in GWP. However, when CF was 60 % the difference between GWP values was 23% less than when CF was 40%. This trend is shown in Figure 7.6.

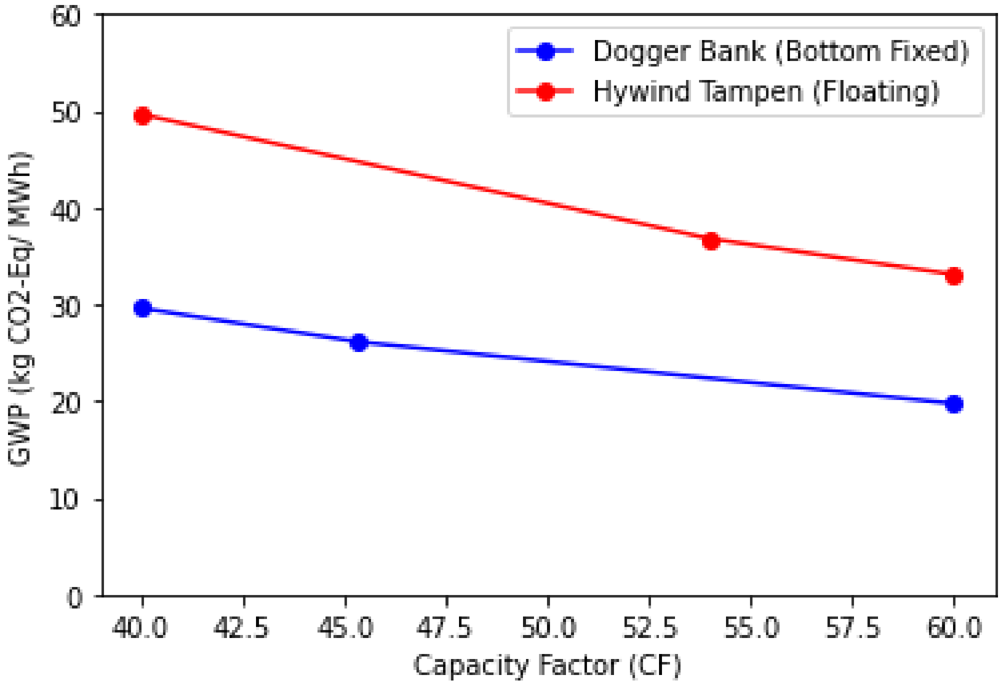

Figure 7.6 The trend of changing of GWP with CF

7.2.2 Lifetime of The Wind Farm

It was anticipated that extending the farm's operational lifespan would lead to a decrease in GWP and other environmental impacts, a hypothesis that was validated by the results. The lifetime of the base case wind farms was initially assumed to be 20 years, the sensitivity analysis was done by calculating impacts for 25,30 and 50 years of lifetime.

7.2.2.1 Lifetime of 25 years

Extending the lifetime of wind farms by 5 years resulted in a reduction of GWP to 22.62 kg CO_2-Eq per MW for Dogger Bank (BFOWF) and 31.67 kg CO_2-Eq per MW for Hywind Tampen (FOWF). As the lifetime increased, the contribution of O&M rose, while the GWP for other life cycle stages decreased.

7.2.2.2 Lifetime of 30 years

Another 5-year extension of the wind farms lifetime resulted in decreasing GWP by 2.28 and 3.41 kg CO2-Eq per MW for bottom fixed and floating cases respectively. Again, The O&M contribution increased, while the GWP for other life cycle stages declined.

7.2.2.3 Lifetime of 50 years

This time an increase of 20 years of lifetime was implemented compared to the previous scenario, which led to a decrease in GWP by 22% and 25 % in bottom fixed and floating cases respectively. As shown in Figure 7.8 the O&M stage became the main contributor to GWP when the wind farm's lifetime reached 50 years.

All 3 lifetime scenarios are compared with the base cases in Figure 7.7. There is a direct correlation between the amount of GWP and the lifetime of the farm.

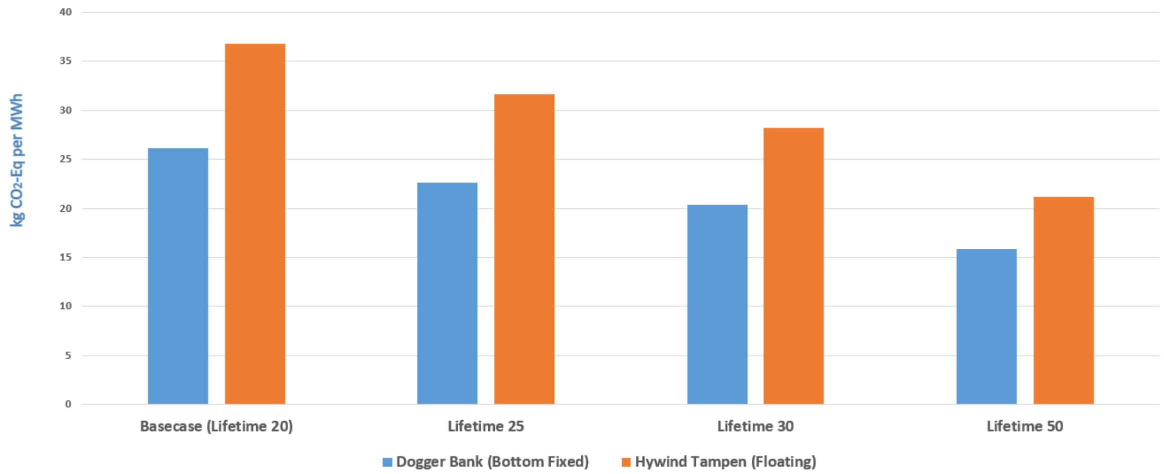

Figure 7.7 Comparing all 3 lifetime scenarios with the base cases.

The comparison of O&M contribution to the total GWP across all lifetime scenarios and base cases is illustrated in Figure 7.8. It is evident that as the lifetime increases, the O&M contribution to the total GWP also rises. It's noteworthy that while the percentages are higher in the bottom-fixed figure, the actual amount of GWP is lower in that scenario.

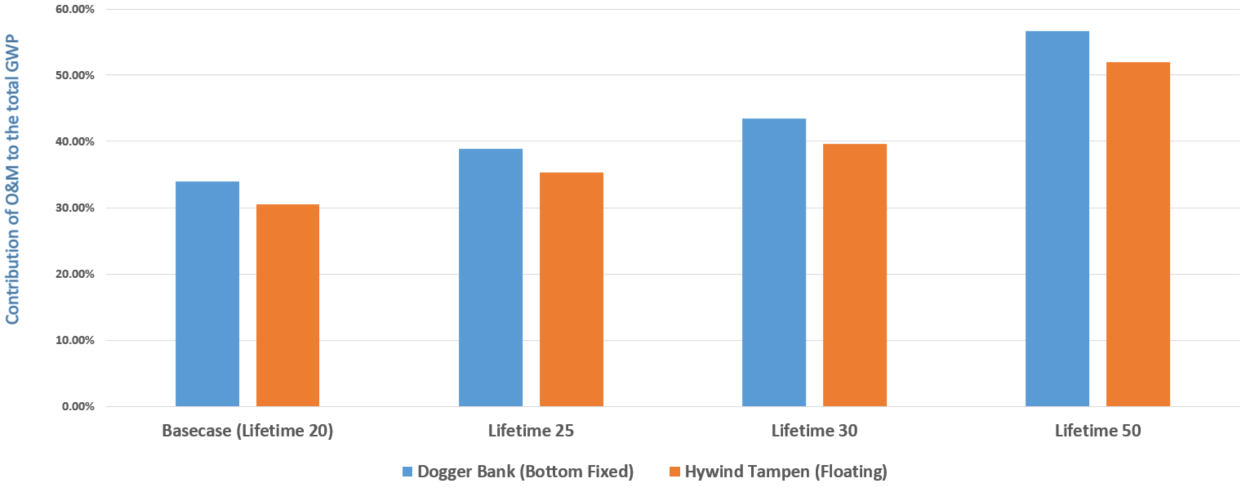

Figure 7.8 The contribution of O&M to the total GWP in all lifetime scenarios.

7.2.3 Moving The Wind Farms Further Offshore

The effect of increasing the distance of the wind farm to the shore was evaluated for two scenarios which will be discussed in this section. Normally when the wind farm is moved further offshore the CF increases due to the availability of stronger and more consistent wind speeds further offshore. However, for simplicity and observing the effect of distance to the shore, this study assumed that when the distance increased the CF remained constant.

7.2.3.1 Distance of 160 km

Increasing the distance of the farm from the port resulted in a higher GWP amount. The findings reveal that extending the distance from 130 to 160 km in the bottom-fixed farm led to a 1% increase in GWP, while in the floating case, a 20 km increase resulted in a 5% rise in GWP, this proves higher sensitivity of floating farm to the distance. This increase in GWP occurred due to increasing the amount of material used for manufacturing export cables, vessels utilized for installation, and vessels used for O&M.

7.2.3.2 Distance of 250 km

Another assessment was conducted by extending the distance by 90 km. The results demonstrate that this extension resulted in a 6% increase in GWP for the bottom-fixed farm, whereas in the floating case, GWP increased by 14%.

The amount of GWP in both distance scenarios are compared with the base cases in Figure 7.9. The changes of GWP with increasing the distance from the port for floating case is much higher than the bottom fixed wind farm.

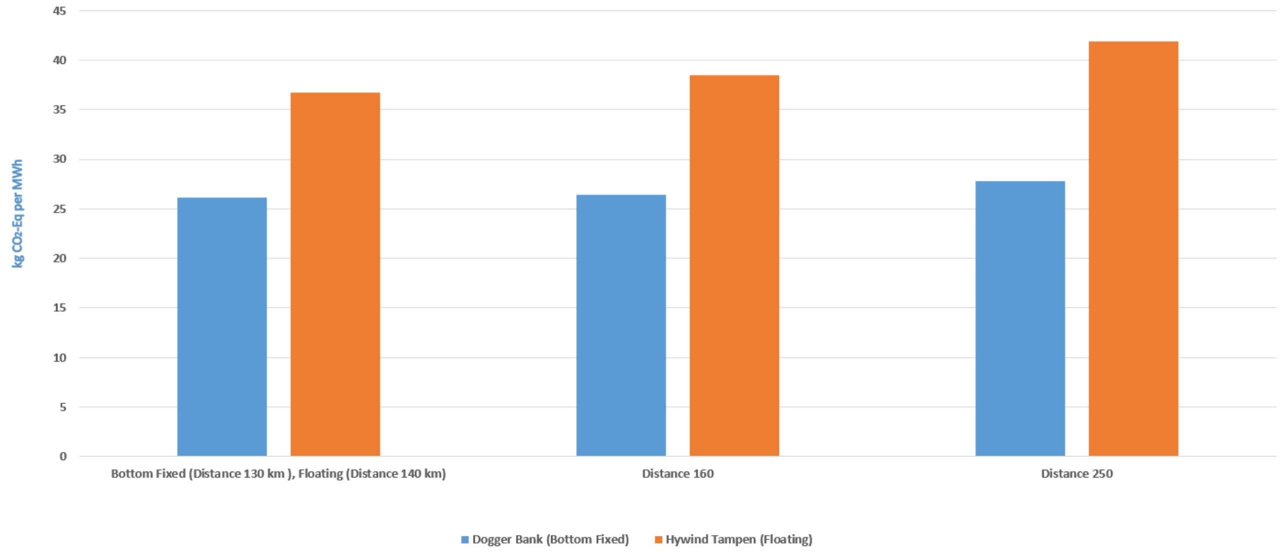

Figure 7.9 Comparing The amount of GWP in both distance scenarios and base cases.

7.2.4 Towing to the Shore for Repair (Floating)

This strategy only applies to the Hywind Tampen FOWF, as it allows for the substructure to be detached from the mooring chains and towed back to the shore for repair in the event of a failure. This strategy was assumed to be done only for major replacement and it was assumed that the other two types of O&M activities (major repair and minor repair) would be conducted at the wind farm location. Results showed that GWP increased by 11.5 % when this strategy was applied. As a result, the best O&M approach for major replacement is operation at the wind farm site instead of towing the wind turbines back to the shore.

Table 7.7 GWP of base case and towing scenario

Scenario	**Total GWP (kg CO_2-Eq/ MWh)**
Base case (Hywind Tampen)	36.78
Towing to the Shore for Repair.	41.01

7.2.5 Overview of All Sensitivity Scenarios

An overview of GWP in all scenarios is provided in Figure 7.10. The highest amount of GWP and the largest difference in GWP amount is when the CF is 40 %. Conversely, the lowest GWP is recorded for a lifetime of 50 years.

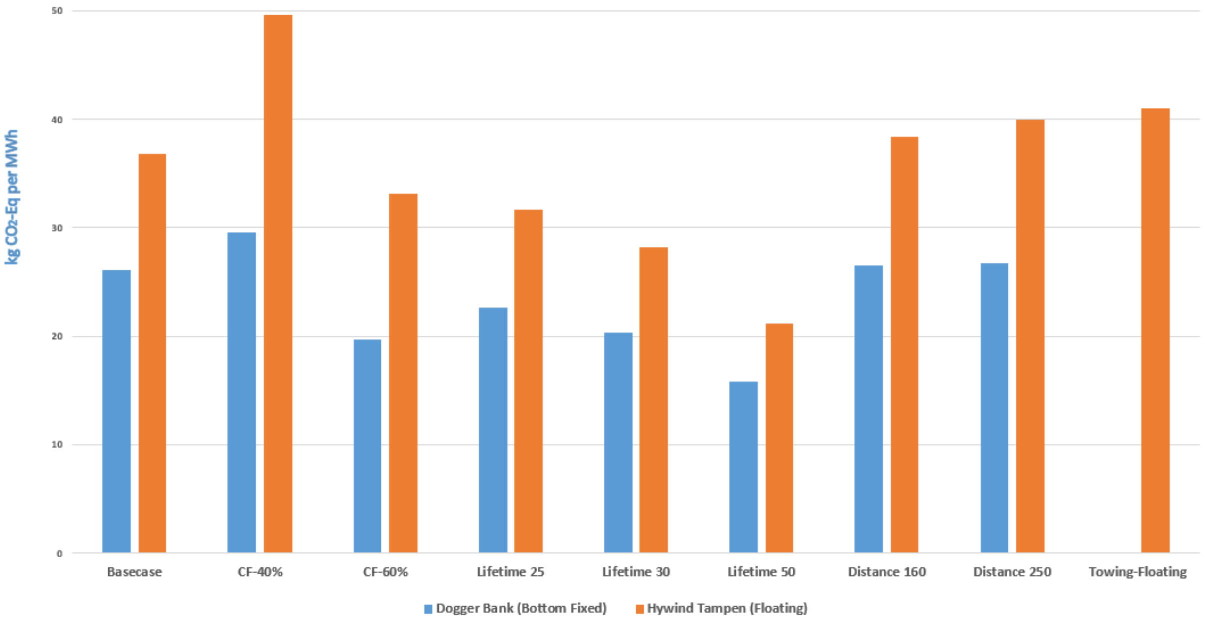

Figure 7.10 An overview of GWP in all scenarios.

The GWP of manufacturing and O&M, which are the stages contributing the most to the total GWP across all scenarios, has been compared in Figure 7.11. When considering a lifetime of 50 years, O&M becomes the primary contributor to GWP, whereas in all other scenarios, manufacturing retains its status as the main contributor.

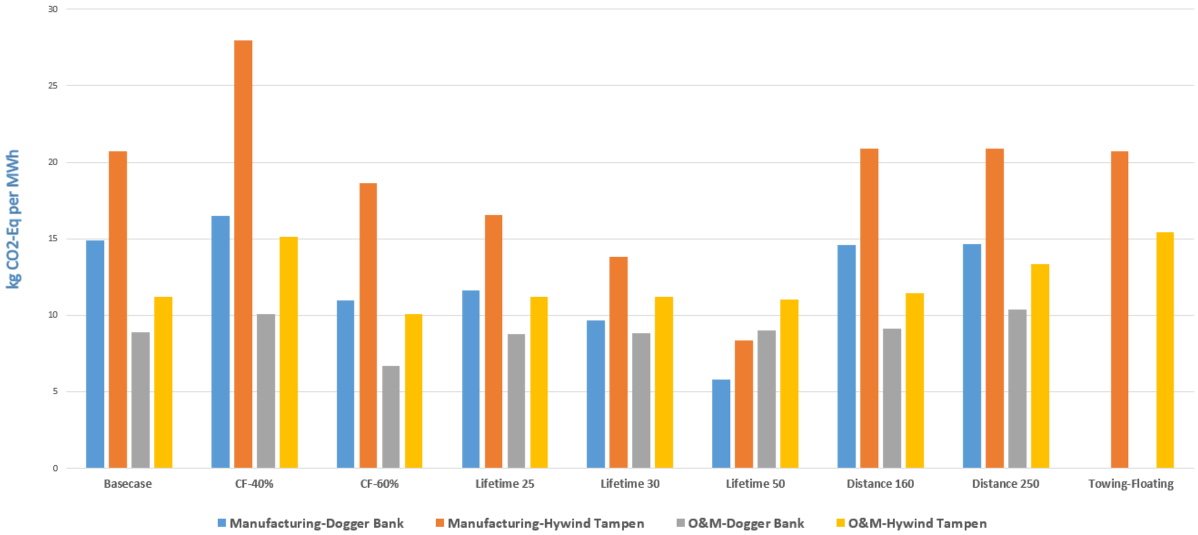

Figure 7.11 The GWP of manufacturing and O&M for all scenarios.

7.3 Comparison with Values in Existing Literature.

7.3.1 Offshore Wind Technology

The results of this study are in good accordance with results from previous studies. The comparison is focused on GWP which is frequently disclosed for energy generation technologies by energy and environmental policies [8].

Based on the methodology proposed by [33] the results of previous studies have been harmonized to ensure comparability with this LCA study, according to Equation (7.1).

$$(\text{kg } CO_2\text{eq}/\text{ MWh})_{harmonized} = (\text{kg } CO_2\text{eq}/\text{ MWh}) \times \frac{CF_{ref}}{CF} \times \frac{LT_{ref}}{LT} \times (1 + (D_{ref} - D) \times R) \qquad (7.1)$$

Where CF is the capacity factor, LT is the actual lifetime, D is the distance to the shore in km and R is the ratio of increase in GWP emission. The reference values (denoted by "ref" in the formula) represent the lifetime, capacity factor, and distance to the shore for the base case scenarios.

In this study, all analyzed sensitivity parameters are considered for harmonization. However, in the original formula proposed by [33], the $(1 + (D_{ref} - D) \times R)$ expression did not exist. The rationale behind adding this expression is that even though LT and CF that had a direct impact on the GWP of all life cycle stages, the effect of distance was not linear, and changing the distance only changed the GWP of some parts of manufacturing (only the length of export cables increased), installation, O&M, and decommissioning. It was observed that with each 1 km increase in distance, GWP for Dogger Bank and Hywind Tampen rose by almost 0.1% and 0.2 % respectively, therefore, the effect of increasing the distance was added in this way. The reference values for the two base case scenarios are shown in Table 7.8 .Thanks to this approach, the comparison will be unaffected by site-specific wind conditions ,assumed lifetime and distance to the shore [33].

Table 7.8 The reference values for the two base case scenarios.

Scenario	CF_{ref} **(%)**	LT_{ref} $(Years)$	D_{ref} **(km)**	**R**
Dogger Bank (BFOWF)	45.3	20	130	0.001
Hywind Tampen (FOWF)	54	20	140	0.002

An overview of the results of existing studies on offshore wind turbines has been provided in

Table 7.9. The harmonized GWP values are provided for both methods: the method proposed by [33] and the method developed in this study. As can be seen, there is a noticeable difference when distance is considered. The value of harmonized GWP using this study's method was observed to be in the range of 13.9 to 49.9 kg CO_2-Eq/ MWh. For studies [27] and [106] it was not possible to obtain harmonized GWP because the value of CF was not given. All these studies used cradle-to-grave method and recycling was inside their boundaries except [8] which partially considered recycling. There was another study by Skår [94] that has not been mentioned in

Table 7.9 as this research only considered the decommissioning stage and the result for their base case scenario was 0.16 kg CO_2-Eq/ MWh which is much less than 1.16 share of decommissioning for bottom-fixed base case scenario of the current study and other existing studies in literature. One reason for this discrepancy could be the fact that in this study and previous research, decommissioning was assumed to be reverse and equivalent to the installation stage. Another reason could be the difference between the lifetime and CF of the base cases of the two studies, the lifetime of the [94] was assumed to be 25 years and nothing has been mentioned about the CF.

The study [8] has concluded that the emission from spar foundation WTs was higher than the semi-submersible WTs whereas the study [41] reached the opposite conclusion. One potential explanation for this inconsistency might be that in [41] only one turbine of each foundation was studied while [8] performed LCA of a wind farm. Another reason could be the difference between the power rating of WTs in the two mentioned studies.

Table 7.9 An overview of the results of existing studies on offshore wind turbines.

WT Power rating (MW)	Number of WTs	Foundation Type	Distance from shore (km)	CF	LT	GWP [7]	Harmonized GWP Without considering distance [7]	Harmonized GWP considering distance[7]	Ref
8	75	Spar Bouy (FOWT)	35	50.00%	25	30.17	26.1	31.5	[40]
15	1	Semi-Submersible steel (FOWT)	30	43.00%	20	32.6	40.9	49.9	[41]
15	1	Spar Bouy concrete (FOWT)	30	43.00%	20	24.3	30.5	37.2	[41]
6	5	Spar Bouy (FOWT)	25	49.40%	25	45.2	39.5	48.6	[8]
9.5	5	Semi-Submersible steel (FOWT)	15	39.60%	25	39.4	43.0	53.7	[8]
14.7	190	Semi-Submersible steel (FOWT)	75	34.35%	30	31	32.5	36.7	[33]
2	1	Barge-Type (FOWT)	Not given	Not given	20	18.6	-	-	[27]
15	94	Semi-Submersible steel (FOWT)	30	52.30%	20	26.3	27.2	33.1	[36]

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[7] Units in kg CO_2-Eq/ MWh

3.6	27	Monopile (BFOWF)	Not given	Not given	25	25	-	-	[106]
5	40	Spar Bouy (FOWT)	50	53.00%	20	11.52	11.7	13.9	[107]
5	6	Jacket foundation (BFOWF)	60	44.00%	20	32	32.9	35.3	[108]

The main contribution to the total GWP belonged to the manufacturing stage in all the studies mentioned in

Table 7.9. The impact from the O&M stage in the study [8] surpasses one-third of the total result (41% for spar and 40.7 for semi-submersible).While the share of O&M in that study is roughly 10% higher than in this study, it remains the only study with a comparable share of O&M. In other studies such as [40], [41], [33] the share of O&M is around 3 to 5 % of the total results. One potential explanation for this difference could be that the mentioned studies have utilized the general flow “transport, freight, sea, ferry - GLO” in ecoinvent database for vessels used for O&M. Also, studies [40], [41] have interpreted failure rate in in a manner that may be considered unrealistic. For instance, [41] has mentioned that a nacelle annual failure rate of 0.012 per turbine per year would result in approximately 24% (0.012 * 20 years) of the nacelles being replaced over the course of the turbine's lifetime. However, this multiplication may not give correct results as the failure rate is not initially given by percentage values. In other words, an annual failure rate of 0.012 was multiplied by the number of turbines and number of years to calculate the total number of failures of each component over the lifetime.

Finally, the power rating of each turbine is another vital parameter that should be considered. A trend for reducing the GWP by increasing the size of the WTs was not observed in the previous research. However, thanks to technological advancements, it's probable that turbines with higher generation capacity could be engineered without a substantial increase in material usage [40]. If the material used in larger wind turbines does not increase significantly, this could lead to a substantial reduction in emissions.

7.3.2 Onshore Wind Technology

There have been many more studies on onshore wind technology compared to offshore wind. However, the GWP in these studies ranges differently from 11 to 123.7 kg CO_2-Eq/ MWh [21]. The study [31] suggests a range of 2.02- 86.5 kg CO2-Eq/ MWh for onshore wind turbines. Another study [109] compared 2 and 3 MW onshore wind turbines with 4 and 6 MW offshore wind turbines and has reported 7 kg CO2-Eq/ MWh for onshore and 11 kg CO_2-Eq/ MWh for offshore wind turbines.

Overall, most onshore wind turbines’ LCA suggests a lower GWP, and environmental impacts compared to offshore technologies. Expanding the size of offshore turbines may not necessarily provide additional advantages compared to onshore counterparts, as it can result in rising costs, complexity, and emissions related to construction and maintenance [31].

7.4 Comparison with Other Energy Technologies

7.4.1 Comparison with Other Renewable Energies

The range of GWP values obtained for all sensitivity scenarios in this study has been compared with the GWP values of other renewable energy sources in Figure 7.12. As stated in previous sensitivity scenarios, for Dogger Bank BFOWF the GWP was in the range of 15.88 to 29.61 kg CO_2-Eq/ MWh and for Hywind Tampen (FOWF) was in the range of 21.22 to 49.65 kg CO_2-Eq/ MWh. The range of GWP values for other energy sectors was obtained from [110]. It is noteworthy that these GWP values are a range of mean GWPs of each energy sector and these amounts vary depending on the location and specific technology used. The figures show that Dogger Bank (BFOWF) in the worst-case scenario with 29.61 kg CO_2-Eq/ MWh slightly surpasses the best-case scenario of both Hydropower and Photovoltaics with GWP of 27.2 and 24.1 kg CO_2-Eq/ MWh respectively. On the other hand, when the LT of Hywind Tampen is considered 50 years, the GWP would be 21.22 kg CO_2-Eq/ MWh which is lower than the lowest GWP of photovoltaics with 24.1 kg CO_2-Eq/ MWh.

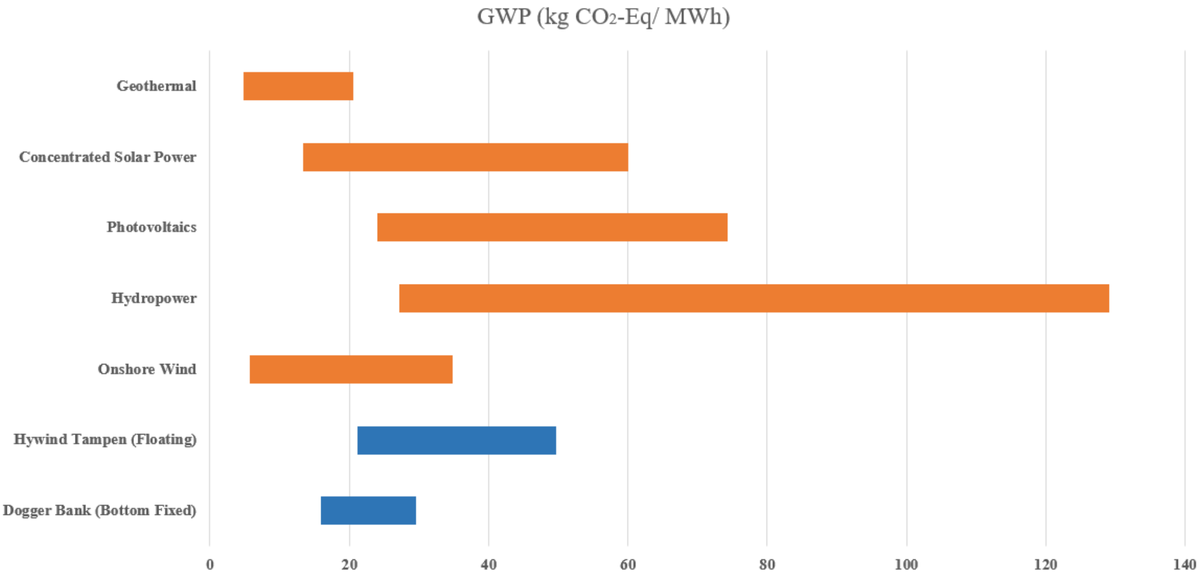

Figure 7.12 Comparing the GWP of this thesis's representative wind farms with other renewable energies [110].

7.4.2 Comparison with Non-Renewable Energies

When comparing the two scenarios in this study with the non-renewable energies, only nuclear energy has a lower GWP while the maximum GWP of both wind farms is by far less than the minimum GWP of the fossil fuels energy sector.

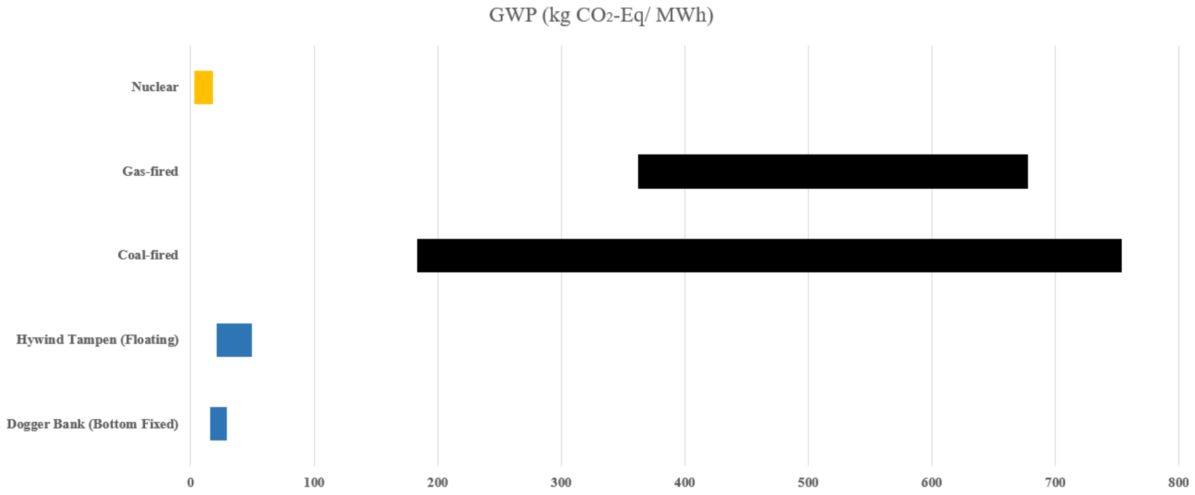

Figure 7.13 Comparing the GWP of this thesis's representative wind farms with non-renewable energies[110].

7.5 Uncertainties

LCA results are typically characterized as deterministic, despite the inherent uncertainties in real-world applications. This uncertainty, which has a considerable impact on the credibility of LCA results, is frequently overlooked [18].There are several uncertainties and challenges associated with conducting LCA on offshore wind farms.

- Data quality and availability: It is important to note that access to specific details of wind turbines and wind farms data is limited due to their commercial sensitivity. This lack of complete transparency necessitates certain assumptions when performing the LCA of offshore wind farms. As a result, it is critical to admit the possibility of some degree of uncertainty regarding data quality.
- Capacity factor (CF): The precise capacity factor remains unknown and is expected to vary annually [40]. However, in this study, CFs were assumed to be constant.
- Lack of proper processes in ecoinvent database: the environmental impacts associated with some activities such as vessels used for installation and decommissioning did not have a specific coefficient in the database and this study opted for ecoinvent's "diesel, burned in diesel-electric generating set" process.
- Failure rates: it was observed that O&M and spare parts significantly contribute to environmental impacts, however, there was a lack of reliable research data regarding the specific failure rates. Furthermore, the assumption was made that failure rates would remain consistent throughout the lifespan of the wind farms, whereas, in reality, the turbine failure rate may fluctuate over time.
- Decommissioning stage assumption: due to lack of time and data availability issues this study followed the approach of most previous studies assuming that the emissions from decommissioning are the reverse and equivalent to the installation stage. Nonetheless, the impacts of decommissioning differ from installation.
- Uncertainty with other assumptions: according to [111] which has categorized uncertainties with LCA methods, assumption and approximations are one of the main

types of uncertainties. In this study many different assumptions were made, however, making these assumptions is an intrinsic part of any LCA research.

7.6 Environmental Impacts on Marine Wildlife

The 18 impact categories reviewed in this study are not the only environmental effects of offshore wind farms and these farms impact the environment in various other ways beyond the scope of this LCA. There is significant concern regarding the impact of wind farms on wildlife, particularly terrestrial birds, and bats, as well as offshore seabirds and marine mammals. [112].In the following, the impacts on marine mammals and seabirds will be briefly discussed.

7.6.1 Impacts on Marine Mammals

Almost all offshore wind farms (OWFs) throughout the world have marine mammals as natural inhabitants. They are subjected to a variety of forces throughout the construction, operating, and decommissioning stages, the most significant of which is noise from pile driving during bottom-fixed foundation installation. Other factors, such as vessel traffic, can significantly increase noise levels. This noise can lead to stress and physical harm. In addition, there is a risk of colliding with service vessels and disrupting suitable habitats. On the other hand, some species may benefit from reef and refuge effects, such as enhanced prey availability around wind farm buildings or reduced fishing pressure and disturbance. Figure 7.14 illustrates the range of impacts that could affect marine mammals throughout the lifespan of a wind farm [112].

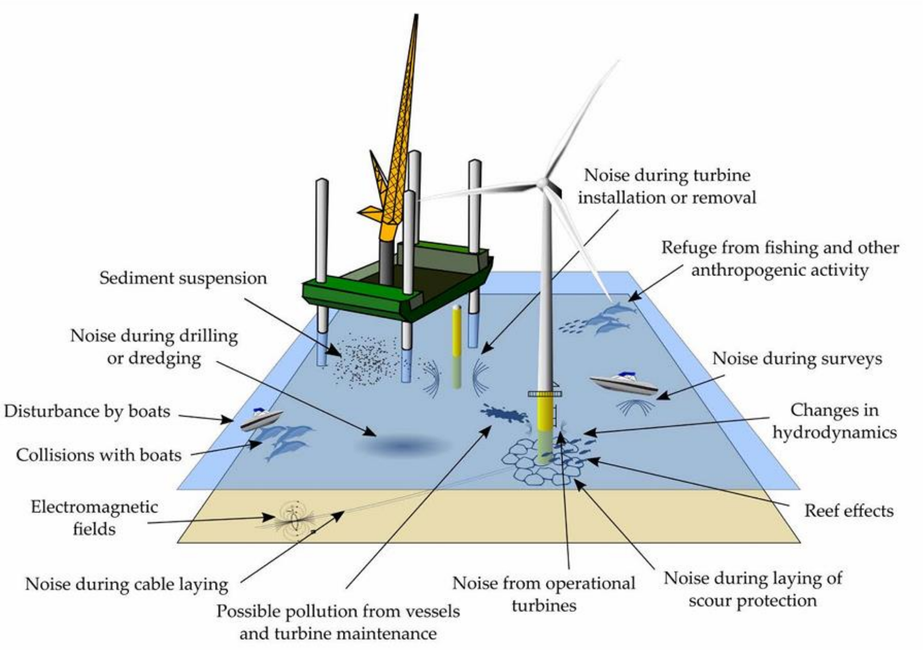

Figure 7.14 The range of impacts that could affect marine mammals throughout the lifespan of a wind farm [112].

7.6.2 Impacts on Seabirds

The proportion of terrestrial bird species and bats migrating over the water is higher than previously thought, especially during fall migration, when large numbers are seen offshore. As a result, the rapid global expansion of offshore wind-generating installations may represent a significant hazard to migrating birds and bats due to collision risk. Birds and bats' behavior around OWFs varies according to intrinsic, environmental, site-specific, and species-specific characteristics. During the day and on clear nights, many bird species avoid OWFs by flying above rotor height or between turbine rows, which has a modest impact on flight energetics and a low collision risk. During adverse weather conditions, birds may fly at lower altitudes, and lighted objects can attract them. As a result, the risk of collision can increase. Furthermore, the enormous surface area planned for OWF projects has raised concerns regarding seabird displacement and habitat loss [112].

Figure 7.15 Flocks of seabirds flying close to an offshore wind farm [112].

8 Conclusion and Recommendations for Further Research

In this thesis, a detailed assessment of the environmental implications associated with two different types of offshore wind farm technologies was conducted. For the first time, a comparative life cycle assessment (LCA) was carried out on two real-world case studies with two different technologies: floating (Hywind Tampen) and bottom-fixed (Dogger Bank). The LCA findings indicated that the Hywind Tampen has higher environmental impacts compared to the Dogger Bank C. For the base case scenarios, the GWP for the floating farm was calculated to be 36.78 kg CO_2-Eq/ MWh while for the bottom-fixed farm, this value was 26.15 kg CO_2-Eq/ MWh.

It was also observed that, in both floating and bottom fixed farms manufacturing stage accounted for almost 57 % of the total GWP emissions, followed closely by the operation and maintenance (O&M) stage. Around 90% of emissions in the O&M stage were due to failures that occurred in wind turbines. To address these challenges, developing, and adopting more sustainable manufacturing techniques for wind turbine components is emphasized. For instance, design strategies that maximize generation capacity per unit of material used could significantly reduce emissions associated with the manufacturing stage. Additionally, increasing wind turbine reliability can reduce the environmental impact of the O&M stage.

Furthermore, the sensitivity of the results to some parameters was examined. The sensitivity analysis results highlighted the capacity factor and lifetime of the farm as significant factors influencing overall environmental impacts.

It is noteworthy that although the results are presented per functional unit to facilitate fair comparison between the two wind farms, the comparison is not solely about floating and bottom-fixed technologies; rather, it compares *two real-world wind farms* utilizing these technologies. The specific environmental impact results are influenced by factors unique to each wind farm (e.g., number of turbines, turbines' power rating, capacity factor, distance to shore). To partially mitigate the effect of these factors, GWP was also calculated based on tones CO_2-Eq per MW per year and the results were 172.5 and 102.6 for floating and bottom-fixed respectively. One reason for this discrepancy could be the fact that bottom-fixed wind turbines' power rating was much larger than the floating wind turbines' power rating.

Ultimately, despite having some emissions and impacts on marine wildlife, offshore wind farms are one of the most promising solutions for global warming and energy security issues. Further investigations and technological advancements will of course make these gigantic wind turbines even more environmentally friendly.

Recommendations for Further Research

Further investigation or enhancement in future research is advised for the following aspects:

- The vessels used for installation and decommissioning significantly contributed to the overall environmental impacts. Therefore, performing an LCA focusing on green energy vessels is recommended.
- Cost-benefit analysis of different life cycle stages of the wind farms was in the initial scope of this thesis work. However, owing to time constraints and issues with the availability of the data, this was not conducted in the current study. Future investigations by scholars or individuals who have access to the cost data of OWFs are highly recommended.
- Analysis of the sensitivity of failure rates: the O&M stage emerged as the second-largest contributor to the total emissions of the examined wind farms. This highlights the importance of conducting a sensitivity analysis regarding failure rates.
- Harmonizing the amount of GWP and other environmental impacts is crucial to be compared to other investigations. However, in the formula proposed in Equation (7.1) it was assumed there was a direct relationship between LT and CF with GWP. Conducting a parametric analysis of the mentioned equation and developing it further could provide the possibility of a fairer comparison of the results across various studies.
- It was assumed that the emissions from decommissioning are the reverse and equivalent to the installation stage. Further investigating the decommissioning stage and performing a sensitivity analysis based on different decommissioning techniques is recommended.
- Utilizing a Monte Carlo simulation method to quantify the impact of uncertainties on emissions is suggested.
- Due to significant uncertainty levels and data availability issues, recycling was excluded from consideration as part of the EOL stage in the present study. Further investigations on this stage i.e. performing a cradle-to-cradle LCA could provide useful insights into the materials utilized for manufacturing OWTs.
- In the current study, two real wind farms were compared; however, the difference between the number of OWTs in each farm was significant, performing a comparative LCA for two wind farms with the same number of WTs could provide valuable information about the effect of number of turbines on the environmental impacts.

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Appendices

Appendix A: Project Description

University of
South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title:
Life Cycle Assessment of Offshore Wind Farms – A Comparative Study of Floating Vs. Fixed Offshore Wind Turbines

USN supervisor: Hadi Amlashi

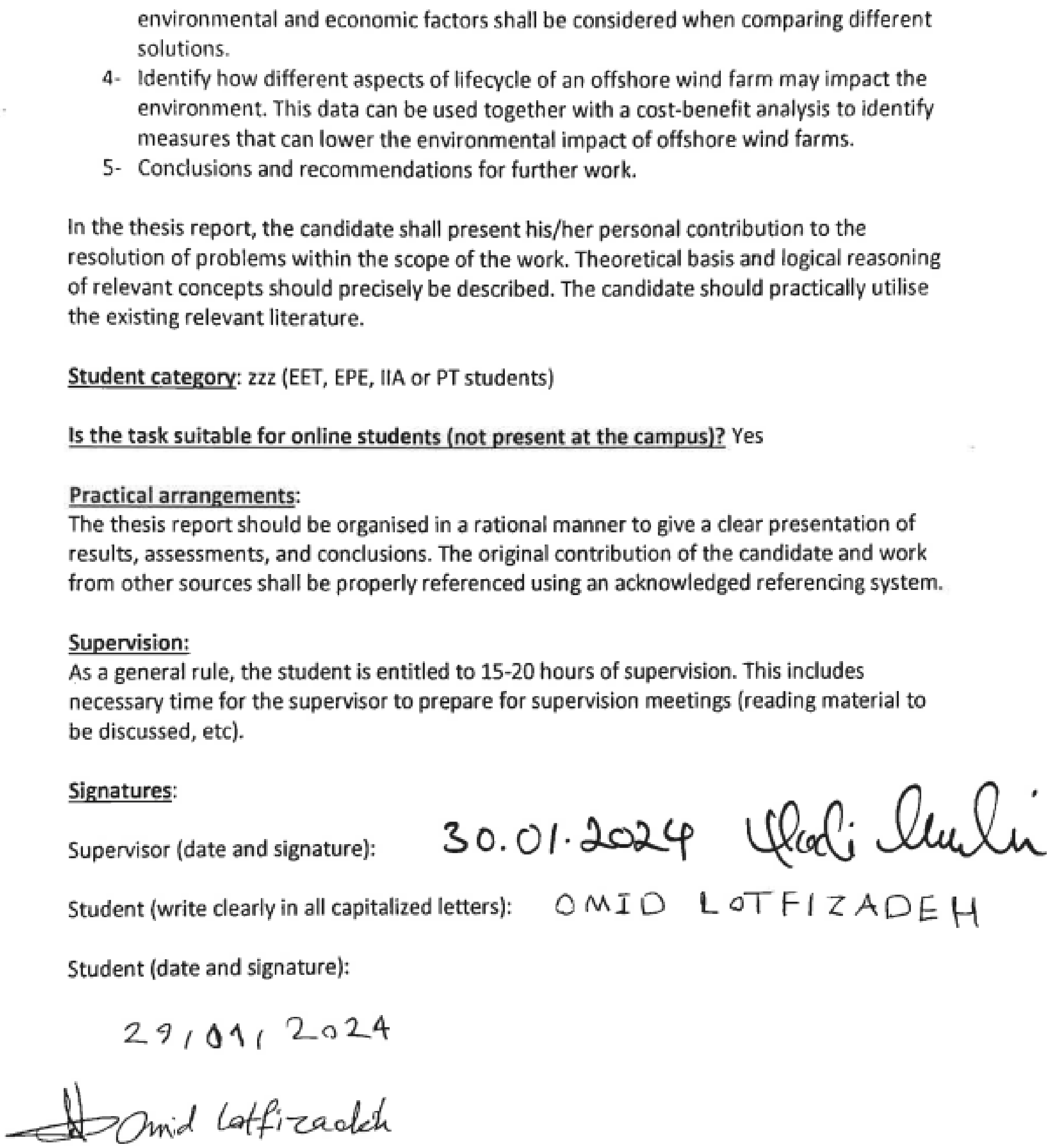
External partner: zzz

Task background:
The world's need for energy is increasing as the population grows and economies develop. This increasing demand for energy puts pressure on finding ways to produce energy in a manner that is sustainable and does not harm the environment. It is important to find solutions that can meet the growing energy demand while minimizing negative impacts on the environment.
Offshore wind power refers to the generation of electricity from wind turbines located in bodies of water, such as oceans or large lakes. Offshore wind power has gained significant attention and investment in recent years as a viable solution to meet the increasing energy demand. There has been a significant increase in the number and size of offshore wind farms installed in various locations around the world. This increase in installed capacity means that more wind turbines are being built and connected to the power grid, allowing for the generation of larger amounts of electricity from offshore wind power.
Like any infrastructure, offshore wind farms have a limited lifespan and eventually reach the end of their operational life. When offshore wind farms reach the end of their life cycle, they need to be decommissioned, which means they are taken out of service and removed from the water. Decommissioning offshore wind farms is a complex process that involves safely shutting down the turbines, disconnecting them from the power grid, and removing them from the water. Decommissioning also involves dismantling and disposing of the various components of the wind turbines, such as the blades, towers, and foundations, in an environmentally responsible manner. The decommissioning process requires careful planning and consideration to ensure that it is done safely, efficiently, and with minimal impact on the surrounding environment.

Task description:

The proposed tasks to be carried out include:
1- Perform a literature review of offshore wind turbine's life cycle and its environmental impacts and develop a holistic understanding of energy balances and emissions over the life cycle of an offshore wind farm, including fabrication, installation, operation and end of life (decommissioning) of the wind farm.
2- Establish a framework for the life cycle assessment of offshore wind farms based on the ISO14040 and ISO14044 standards. Dataset and LCA analysis to be presented with the help of openLCA software.
3- Conduct a comparative analysis of different offshore wind solutions (floating vs. bottom-fixed). A comparison of different turbine sizes, different foundation, farm locations, and different techniques for decommissioning shall be done. Both

Appendix A (Continued)



environmental and economic factors shall be considered when comparing different solutions.

4- Identify how different aspects of lifecycle of an offshore wind farm may impact the environment. This data can be used together with a cost-benefit analysis to identify measures that can lower the environmental impact of offshore wind farms.

5- Conclusions and recommendations for further work.

In the thesis report, the candidate shall present his/her personal contribution to the resolution of problems within the scope of the work. Theoretical basis and logical reasoning of relevant concepts should precisely be described. The candidate should practically utilise the existing relevant literature.

Student category: zzz (EET, EPE, IIA or PT students)

Is the task suitable for online students (not present at the campus)? Yes

Practical arrangements:
The thesis report should be organised in a rational manner to give a clear presentation of results, assessments, and conclusions. The original contribution of the candidate and work from other sources shall be properly referenced using an acknowledged referencing system.

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature): 30.01.2024

Student (write clearly in all capitalized letters): OMID LOTFIZADEH

Student (date and signature):

29/01/2024

Omid Lotfizadeh

Appendix B: Reference websites utilized to find a proper literature review method.

Source Number	Website Address
(1)	https://libguides.csu.edu.au/review/Types
(2)	https://research-methodology.net/research-methodology/types-literature-review/
(3)	https://www.ncbi.nlm.nih.gov/books/NBK481583/
(4)	https://www.crowdwriter.com/blog/types-of-literature-review
(5)	https://guides.hsict.library.utoronto.ca/c.php?g=705263
(6)	https://www.lib.uwo.ca/tutorials/typesofliteraturereviews/index.html
(7)	https://utopia.ut.edu/literaturereviews/types
(8)	https://pressbooks.online.ucf.edu/sandboxstrategies3/chapter/types-of-literature-reviews/
(9)	https://libguides.und.edu/literature-reviews/types
(10)	https://uow.libguides.com/systematic-review/types-of-systematic-reviews
(11)	https://encyclopedia.pub/entry/43489
(12)	https://guides.nyu.edu/pico/types-of-literature-reviews
(13)	https://ctl.unm.edu/assets/docs/resources/literature-reviews.pdf
(14)	https://libguides.usc.edu/writingguide/literaturereview
(15)	https://www.ardaconference.com/blog/all-you-need-to-know-about-literature-review-and-its-types/
(16)	https://dissertationbydesign.com/four-ways-to-structure-your-literature-review/
(17)	https://guides.lib.ua.edu/literaturereview/what
(18)	https://researchmethod.net/literature-review/
(19)	https://laneguides.stanford.edu/systematicreviews/knowledgesynthesis
(20)	https://hslguides.osu.edu/systematic_reviews/choose

Appendix C: Results; Heatmap of the contribution of each life cycle stage to the total GWP

Table C1. A heatmap of the contribution of each life cycle stage to the total GWP for CF =40%.

	Dogger Bank (Bottom Fixed)		**Hywind Tampen (Floating)**	
Stage	**Contribution (%)**	**GWP (kg CO_2-Eq/ MWh)**	**Contribution (%)**	**GWP (kg CO_2-Eq/ MWh)**
Wind Turbine Manufacturing	43.84%	12.98	26.79%	13.30
Substructure Manufacturing	11.84%	3.51	26.73%	13.27
Mooring system Manufacturing	-	-	2.82%	1.40
Power Transmission Manufacturing	1.36%	0.40	1.32%	0.66
Transportation	0.13%	0.04	0.07%	0.03
Installation	4.44%	1.31	5.91%	2.93
O & M vessel	12.60%	3.73	16.27%	8.08
O & M spare parts	21.35%	6.32	14.18%	7.04
Decommissioning	4.44%	1.31	5.91%	2.93
Total	100.00%	29.61	100.00%	49.65

Table C.2. heatmap of the contribution of each life cycle stage to the total GWP for CF =60

	Dogger Bank (Bottom Fixed)		**Hywind Tampen (Floating)**	
Stage	**Contribution (%)**	**GWP (kg CO_2-Eq/ MWh)**	**Contribution (%)**	**GWP (kg CO_2-Eq/ MWh)**
Wind Turbine Manufacturing	43.84%	8.65	26.79%	8.87
Substructure Manufacturing	11.84%	2.34	26.73%	8.85
Mooring system Manufacturing	-	-	2.82%	0.93
Power Transmission Manufacturing	1.36%	0.27	1.32%	0.44
Transportation	0.13%	0.03	0.07%	0.02
Installation	4.44%	0.88	5.91%	1.96
O & M vessel	12.60%	2.49	16.27%	5.39
O & M spare parts	21.35%	4.21	14.18%	4.69
Decommissioning	4.44%	0.88	5.91%	1.96
Total	100.00%	19.74	100.00%	33.10

Appendix C (Continued)

Table C.3. Heatmap of the contribution of each stage of life cycle stages to the total GWP for lifetime of 25 years.

	Dogger Bank (Bottom Fixed)		**Hywind Tampen (Floating)**	
Stage	**Contribution (%)**	**GWP (kg CO$_2$-Eq/ MWh)**	**Contribution (%)**	**GWP (kg CO$_2$-Eq/ MWh)**
Wind Turbine Manufacturing	40.54%	9.17	24.90%	7.89
Substructure Manufacturing	10.95%	2.48	24.84%	7.87
Mooring system Manufacturing	-	-	2.62%	0.83
Power Transmission Manufacturing	1.32%	0.30	1.23%	0.39
Transportation	0.10%	0.02	0.07%	0.02
Installation	4.10%	0.93	5.49%	1.74
O & M vessel	16.21%	3.67	18.90%	5.99
O & M spare parts	22.68%	5.13	16.46%	5.21
Decommissioning	4.10%	0.93	5.49%	1.74
Total	100.00%	22.62	100.00%	31.67

Table C.4. Heatmap of the contribution of each stage of life cycle stages to the total GWP for lifetime of 30 years.

	Dogger Bank (Bottom Fixed)		**Hywind Tampen (Floating)**	
Stage	**Contribution (%)**	**GWP (kg CO$_2$-Eq/ MWh)**	**Contribution (%)**	**GWP (kg CO$_2$-Eq/ MWh)**
Wind Turbine Manufacturing	37.46%	7.62	23.24%	6.57
Substructure Manufacturing	10.12%	2.06	23.19%	6.55
Mooring system Manufacturing	-	-	2.45%	0.69
Power Transmission Manufacturing	1.16%	0.24	1.15%	0.32
Transportation	0.17%	0.03	0.07%	0.02
Installation	3.79%	0.77	5.13%	1.45
O & M vessel	16.15%	3.28	21.17%	5.98
O & M spare parts	27.36%	5.57	18.47%	5.22
Decommissioning	3.79%	0.77	5.13%	1.45
Total	100.00%	20.34	100.00%	28.26

Appendix C (Continued)

Table C.5. Heatmap of the contribution of each stage of life cycle stages to the total GWP for lifetime of 50 years.

	Dogger Bank (Bottom Fixed)		**Hywind Tampen (Floating)**	
Stage	**Contribution (%)**	**GWP (kg CO2-Eq/ MWh)**	**Contribution (%)**	**GWP (kg CO2-Eq/ MWh)**
Wind Turbine Manufacturing	28.77%	4.57	18.65%	3.96
Substructure Manufacturing	7.77%	1.23	18.61%	3.95
Mooring system Manufacturing	-	-	1.97%	0.42
Power Transmission Manufacturing	0.89%	0.14	0.55%	0.12
Transportation	0.14%	0.02	0.09%	0.02
Installation	2.91%	0.46	4.11%	0.87
O & M vessel	21.59%	3.43	27.24%	5.78
O & M spare parts	35.02%	5.56	24.67%	5.23
Decommissioning	2.91%	0.46	4.11%	0.87
Total	100.00%	15.88	100.00%	21.22

Table C.6. Heatmap of the contribution of each stage of life cycle stages to the total GWP for distance of 160 km.

	Dogger Bank (Bottom Fixed)		**Hywind Tampen (Floating)**	
Stage	**Contribution (%)**	**GWP (kg CO2-Eq/ MWh)**	**Contribution (%)**	**GWP (kg CO2-Eq/ MWh)**
Wind Turbine Manufacturing	43.38%	11.47	25.76%	9.90
Substructure Manufacturing	11.72%	3.10	25.70%	9.88
Mooring system Manufacturing	-	-	2.71%	1.04
Power Transmission Manufacturing	1.46%	0.39	4.36%	1.68
Transportation	0.14%	0.04	0.05%	0.02
Installation	4.39%	1.16	5.83%	2.24
O & M vessel	13.40%	3.54	16.13%	6.20
O & M spare parts	21.12%	5.59	13.63%	5.24
Decommissioning	4.39%	1.16	5.83%	2.24
Total	100.00%	26.45	100.00%	38.44

Appendix C (Continued)

Table C.7.Heatmap of the contribution of each stage of life cycle stages to the total GWP for distance of 250km.

	Dogger Bank (Bottom Fixed)		**Hywind Tampen (Floating)**	
Stage	**Contribution (%)**	**GWP (kg CO2-Eq/ MWh)**	**Contribution (%)**	**GWP (kg CO2-Eq/ MWh)**
Wind Turbine Manufacturing	41.37%	11.52	23.73%	9.94
Substructure Manufacturing	11.17%	3.11	23.68%	9.91
Mooring system Manufacturing	-	-	2.50%	1.05
Power Transmission Manufacturing	1.72%	0.48	6.24%	2.61
Transportation	0.13%	0.04	0.04%	0.02
Installation	4.19%	1.17	5.96%	2.50
O & M vessel	17.09%	4.76	19.33%	8.09
O & M spare parts	20.14%	5.61	12.56%	5.26
Decommissioning	4.19%	1.17	5.96%	2.50
Total	100.00%	27.84	100.00%	41.87

Appendix D: Python codes for Figure 7.6

```
Created on Sat May 4 10:09:03 2024

@author: Omid Lotfizadeh
"""
#Master Thesis
#Capacity Factor sensitivity analysis
import matplotlib.pyplot as plt

# Dogger Bank (Bottom Fixed) Data
x_dogger = [40, 45.3, 60.00]
y_dogger = [29.61, 26.15, 19.74]

# Data for Hywind Tampen (Floating) Data
x_hywind = [40, 54, 60.00]
y_hywind = [49.65, 36.78, 33.1]

# Plot
plt.plot(x_dogger, y_dogger, marker='o', color='blue', label='Dogger Bank (Bottom Fixed)')
plt.plot(x_hywind, y_hywind, marker='o', color='red', label='Hywind Tampen (Floating)')

# Axis labels
plt.xlabel('Capacity Factor (CF)')
plt.ylabel('GWP (kg CO2-Eq/ MWh)')  # Updated Y-axis label

# Y-axis limits
plt.ylim(0, 60)

# Legend
plt.legend()
plt.show()
```

Appendix E: The openLCA® results for 18 impact categories

Table E.1. Dogger Bank-BFOWF-Basecase

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.103518
climate change - global warming potential (GWP100)	kg CO2-Eq	26.14683
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.23039
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	2.988757
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	234.152
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	6.860634
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.007898
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.013893
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	14.44264
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	36.57688
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.071724
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.662786
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	88.16551
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.23E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.058363
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.124996
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.128654
water use - water consumption potential (WCP)	m3	0.243783

Appendix E (Continued)

Table E.2. Dogger Bank-BFOWF-CF 40 %

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.117234499
climate change - global warming potential (GWP100)	kg CO2-Eq	29.61128953
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.525916697
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	3.384767792
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	265.17713
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	7.769668072
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.008944572
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.015733752
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	16.35629051
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	41.42332169
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.213727342
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.750605553
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	99.84743478
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.39445E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.066095732
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.141558193
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.145700782
water use - water consumption potential (WCP)	m3	0.276084688

Appendix E (Continued)

Table E.3. Dogger Bank-BFOWF-CF 60 %

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.078156
climate change - global warming potential (GWP100)	kg CO2-Eq	19.74086
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.683944
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	2.256512
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	176.7848
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	5.179779
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.005963
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.010489
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	10.90419
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	27.61555
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.809152
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.500404
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	66.56496
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	9.3E-06
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.044064
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.094372
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.097134
water use - water consumption potential (WCP)	m3	0.184056

Appendix E (Continued)

Table E.4. Dogger Bank-BFOWF-Distance 160 km

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.105325
climate change - global warming potential (GWP100)	kg CO2-Eq	26.45104
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.242182
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	3.004079
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	234.9544
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	6.945633
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.00793
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.013916
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	14.47513
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	36.71872
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.074956
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.664875
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	88.27557
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.25E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.059391
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.128739
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.13246
water use - water consumption potential (WCP)	m3	0.244455

Appendix E (Continued)

Table E.5. Dogger Bank-BFOWF-Distance 250 km

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.113667
climate change - global warming potential (GWP100)	kg CO2-Eq	27.84161
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.291338
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	3.067789
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	238.2425
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	7.338636
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.008051
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.013998
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	14.59111
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	37.27468
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.087265
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.672855
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	88.61213
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.34E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.064136
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.146339
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.150357
water use - water consumption potential (WCP)	m3	0.246933

Appendix E (Continued)

Table E.6. Dogger Bank-BFOWF-LT 25

Impact category	Reference unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.090313
climate change - global warming potential (GWP100)	kg CO2-Eq	22.61677
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.881981
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	2.521227
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	198.0869
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	5.957142
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.006631
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.012658
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	11.99788
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	31.04608
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.90965
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.577353
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	80.68512
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.1E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.050467
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.110481
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.113653
water use - water consumption potential (WCP)	m3	0.21556

Appendix E (Continued)

Table E.7. Dogger Bank-BFOWF-LT 30

Impact category	Reference unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.082
climate change - global warming potential (GWP100)	kg CO2-Eq	20.34117
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.65206
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	2.212564
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	174.1923
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	5.377239
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.005791
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.011837
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	10.37114
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	27.38087
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.802035
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.52068
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	75.69899
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.02E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.045485
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.101898
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.104764
water use - water consumption potential (WCP)	m3	0.196822

Appendix E (Continued)

Table E.8. Dogger Bank-BFOWF-LT 50

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.065964
climate change - global warming potential (GWP100)	kg CO2-Eq	15.88315
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.194939
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	1.59873
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	126.5678
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	4.244347
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.004115
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.010194
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	7.120717
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	20.0746
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.587277
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.407612
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	65.71133
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	8.56E-06
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.03586
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.086051
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.088328
water use - water consumption potential (WCP)	m3	0.159428

Appendix E (Continued)

Table E.9. Hywind Tampen-FOWF-Base case

Impact category	Reference unit	Bottom Fixed	Floating
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.10	0.15
climate change - global warming potential (GWP100)	kg CO2-Eq	26.15	36.78
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.23	2.93
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	2.99	3.90
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	234.15	305.75
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	6.86	8.75
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.01	0.01
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.01	0.01
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	14.44	15.89
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	36.58	46.71
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.07	1.01
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.66	0.72
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	88.17	71.09
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	0.00	0.00
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.06	0.08
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.12	0.21
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.13	0.21
water use - water consumption potential (WCP)	m3	0.24	0.23

Appendix E (Continued)

Table E.10. Hywind Tampen-FOWF-CF 40 %

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.202080263
climate change - global warming potential (GWP100)	kg CO2-Eq	49.65266078
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	3.951486007
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	5.270806201
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	412.7640062
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	11.81705902
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.013257548
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.015563849
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	21.45583629
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	63.05353874
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.366430142
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.973094626
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	95.97637273
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	2.0205E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.109687545
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.283423217
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.290244306
water use - water consumption potential (WCP)	m3	0.308553414

Appendix E (Continued)

Table E.11. Hywind Tampen-FOWF-CF 60 %

Impact category	Reference unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.134723
climate change - global warming potential (GWP100)	kg CO2-Eq	33.10215
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.634335
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	3.513885
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	275.1767
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	7.878147
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.008838
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.010376
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	14.30391
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	42.0358
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.910956
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.648731
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	63.98425
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.35E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.073126
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.188954
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.193502
water use - water consumption potential (WCP)	m3	0.205703

Appendix E (Continued)

Table E.12. Hywind Tampen-FOWF-Distance 160 km

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.157163373
climate change - global warming potential (GWP100)	kg CO2-Eq	38.4376536
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.995518742
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	3.994584212
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	309.1514393
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	9.15395843
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.010233197
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.011623326
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	16.18050466
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	47.99910165
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.035161291
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.739546186
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	71.44379384
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.54806E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.084930724
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.218162007
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.223358915
water use - water consumption potential (WCP)	m3	0.234772248

Appendix E (Continued)

Table E.13. Hywind Tampen-FOWF-Distance 250 km

mpact category	Reference unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.176488
climate change - global warming potential (GWP100)	kg CO2-Eq	41.87459
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	3.113982
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	4.148681
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	315.9079
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	10.08362
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.010674
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.011747
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	16.49236
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	49.62363
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.06524
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.762114
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	71.74301
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.74E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.09555
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.254543
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.260348
water use - water consumption potential (WCP)	m3	0.241787

Appendix E (Continued)

Table E.14. Hywind Tampen-FOWF-LT 25

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.131846
climate change - global warming potential (GWP100)	kg CO2-Eq	31.66503
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.576821
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	3.430914
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	267.1783
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	7.62593
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.008346
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.010499
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	13.39736
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	40.99934
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.864519
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.624607
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	65.12077
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.35E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.071341
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.187174
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.191604
water use - water consumption potential (WCP)	m3	0.201407

Appendix E (Continued)

Table E.15. Hywind Tampen-FOWF-LT 30

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.120008
climate change - global warming potential (GWP100)	kg CO2-Eq	28.26368
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.347295
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	3.12049
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	241.8686
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	6.87612
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.007371
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.009835
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	11.74602
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	37.25943
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.766751
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.561255
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	61.30621
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.24E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.064762
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.172021
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.176037
water use - water consumption potential (WCP)	m3	0.183371

Appendix E (Continued)

Table E.16. Hywind Tampen-FOWF-LT 50

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.094793
climate change - global warming potential (GWP100)	kg CO2-Eq	21.21658
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.874275
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	2.481506
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	190.0845
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	5.307114
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.005394
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.00846
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	8.411655
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	29.59853
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.568681
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.432294
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	53.37351
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.03E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.050731
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.138479
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.141613
water use - water consumption potential (WCP)	m3	0.146896

Appendix E (Continued)

Table E.17. Hywind Tampen-FOWF-Towing strategy

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.176406
climate change - global warming potential (GWP100)	kg CO2-Eq	41.01295
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	3.055026
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	4.068926
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	313.8502
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	9.973957
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.010047
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.011625
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	16.06133
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	47.90371
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.035832
land use - agricultural land occupation (LOP)	m2*a crop-Eq	0.736219
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	71.13728
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	1.79E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.096604
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.269478
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.275516
water use - water consumption potential (WCP)	m3	0.232732

Appendix F: Supplementary Materials

Including:

1- Inventory

2- General Calculations

3- Electricity to the grid calculations

Please see the 3 Excel files on the below DOI:

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