**Hovedoppgave**

**NTNU**
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for marin teknikk

Elias Holmboe Skår

# An Assessment of the Global Warming Potential of Marine Operations Related to Decommissioning of Offshore Wind Farms

Hovedoppgave i Marin Teknikk / Marine Technology
Veileder: Gary Harald Isaksen
Juni 2022

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# Description of Master Thesis

## Introduction

The goal of the thesis is to develop an 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. The thesis will focus on decommissioning and end-of-life in particular, as a literature review conducted last semester showed few other papers have focused on this phase of an offshore windfarm's life cycle.

## Methods

A life cycle assessment (LCA) is a method for evaluating environmental impacts of a product over its lifetime. The ISO14040 and ISO14044 standards will provide the framework for the life cycle assessment conducted in this thesis. Emission and product data will be obtained from databases provided by NTNU through the SimaPro software. Final calculations and bookkeeping will also be done using SimaPro.

## Subjects of Study

A comparative analysis of different offshore wind solutions will be conducted. A comparison of different turbine sizes, farm locations, foundations (floating or fixed), and different techniques for decommissioning will be done. Both environmental and economic factors will be considered when comparing different solutions.

The thesis will focus on new developments in the offshore wind industry, such as large diameter turbines, large scale farms, and moving the farms farther offshore. The thesis will study the effect these factors have on the environment, especially on operations related to the end-of-life of the farm.

## Research Goals

The goal of the thesis is to identify how different aspects of the eol/operational lifecycle of an offshore wind farm impact the environment, and how differences in location, scale, decommissioning techniques, and different turbine types effect the environment differently. This data can be used together with a cost-benefit analysis to identify measures that can lower the environmental impact of offshore wind farms.

## Previous Work/Studies

Previous studies or life cycle assessments of offshore wind farms and turbines have been conducted by several authors belonging to different institutions, however most of these have focused mainly on the production and sourcing of materials for the turbines. Few of them consider the effects of decommissioning beyond just recycling the material.

# Preface

This thesis is written as part of the M.Sc. degree in Marine Technology at the Norwegian University of Science and Technology. It has been written the spring semester of 2022.

This thesis is a continuation of work performed in the project thesis written in the autumn semester of 2021. The project thesis was a literature review of life cycle assessments on offshore wind. The project thesis has helped preparing for the assessment conducted in this thesis.

The purpose of the thesis was to investigate the global warming impact of the decommissioning phase of an offshore wind farm life cycle. The work has been time consuming, and the data collection has been especially hard to manage.

I would like to thank my supervisor Gary Harald Isaksen for assisting and giving great advice throughout the work on both this thesis, and the project thesis last semester. It has been a steep learning curve, but the work has provided me with good insight into offshore wind operations, as well as environmental impact assessments.

Son, 30th June 2022

# Abstract

The world is in constant need for more energy, and at the same time, this energy needs to be produced with as little environmental impact as possible. Offshore wind power has been put forward as a solution to this dilemma, and the capacity of installed offshore wind power has exploded in the last decades. Of course, at some point, these wind farms will have reached the end of their life cycle, and will need to be powered down and removed.

The aim of this thesis has been to investigate the global warming potential of marine operations related to the decommissioning activities of offshore wind farm. Some work has been done on this previously, however, this has mostly been done in the form of life cycle assessments that have considered the entire life cycle, putting little focus on marine operations in general.

In this thesis, several wind farm cases and scenarios have been developed, in order to identify what part of the decommissioning process contributes the most to global warming, and what methods can be employed to potentially lower these contributions. A basecase, reflecting an "average" or typical modern offshore wind farm was established, consisting of 100 turbines with a rating of 8 MW installed on monopiles. This basecase was used as a basis for comparisons, in order to identify what affects greenhouse gas emissions the most. The effect types of foundations used in the wind farms, the size and number of turbines, how cables were removed, and new potential technologies have on greenhouse gas emissions have been assessed.

All marine operations related to the removal and decommissioning of an offshore wind farm was included in the assessment done in this thesis. Preparation of the seabed before foundation removal, the cutting and removal of the foundations, the disassembly of the wind turbines, the removal of cables, and the final transportation of all components back to shore.

The results show that for a typical modern offshore wind farm, the contribution to global warming from decommissioning activities is 0.16 kg $CO_2$-eq / MWh. The types of foundations that were used in the wind farm had the biggest effect on the environmental impact, with decommissioning of jacket and gravity based foundations contributing more than double to global warming, compared with decommissioning of monopile foundations. However, the results also showed that it was possible to significantly reduce the impact by utilizing new technologies and specialized vessels.

An assessment was also conducted on floating offshore wind farms, a relatively new development, with only pilot projects having been completed so far. However, the results show that this type of offshore wind farm, a larger part of the life cycle needs to be included in the assessment in order to achieve a result that is comparable to fixed offshore wind farms.

# Sammendrag

Målet for denne oppgaven har vært å undersøke effekten av marine operasjoner knyttet til fjerning og avvikling av havvind. Studier som undersøker utslipp av drivhusgasser fra hele livssyklusen til havvindparker har blitt utført tidligere, men disse har fokusert på hele livssyklusen til havvind, og har ikke hatt et spesielt fokus hverken på marine operasjoner, eller sluttfasen av livssyklusen generelt.

I denne oppgaven har flere scenario og typer av havvindsparker blitt utviklet, for å identifisere hvilken del av avviklingsprossesen som påvirker miljøet mest. I tillegg har det blitt undersøkt hvilke metoder som kan brukes for å senke den eventuelle påvirkningen mest mulig. Et grunnscenario, som representer en gjennomsnittlig eller typisk moderne havvindspark har blitt utviklet, og består av 100 stykker 8 MW turbiner, montert på pålefundament. Denne havvindsparken ble brukt som sammenlikningsgrunnlag for å finne hvilke faktorer som påvirker miljøet mest. Effekten av forskjellige typer fundament, størrelsen og antallet turbiner, hvordan fjerning av kabler foregikk, og potensielle nye teknologier har på drivhusgassutslipp har blitt undersøkt.

Alle marine operasjoner knyttet til fjerning og avvikling av havvindsparker har blitt inkludert i undersøkelsen gjennomført i denne oppgaven. Det inkluderer forberedelser av havbunnen før fjerning av fundament, kutting og løft av fundament, demontering av vindturbiner, fjerning av kabler, og transport tilbake til land for videre demontering.

Resultatene viste at en typisk moderne havvindspark slipper ut 0.16 kg $CO_2$-ekvivalenter med drivhusgasser under avviklingen. Hva slags fundament som brukes hadde størst innvirkning på resultatene, fjerning av fagverksplattformer og gravitasjonsplatformer forurenset mer enn dobbelt så mye som fjerning av pålefundament. Men, resultatene viste også at det var mulig å redusere disse utslippene ved bruk av ny teknologi, og spesiallagde fartøy.

En undersøkelse av flytende havvind, en relativt ny utvikling, er også blitt gjennomført. Kun pilotprosjekter er blitt ferdigstilt så langt. Resultatene viser at for at avvikling av flytende anlegg skal kunne sammenliknes med bunnfaste anlegg, så må en større del av livssyklusen være med i undersøkelsen.

# Glossary

| | |
|---|---|
| **GHG** | **Green house gas(es)** |
| **GWP** | Global Warming Potential |
| **ISO** | International organisation for standardisation |
| **LCA** | Life Cycle Assessment |
| **LCIA** | Life Cycle Inventory Assessment |
| **SPIV** | Self Propelled Installation Vessel |
| **BOEMRE** | Bureau of Safety and Environmental Enforcement |
| **WTG** | Wind Turbine Generator |
| **MCR** | Maximum continuous rating |
| **DP** | Dynamic Positioning |
| **ROV** | Remotely operated vessel |
| **WOW** | Waiting on Weather |
| **HAWT** | Horizontal Axis Wind Turbine |
| **GBF** | Gravity Based Foundation |
| **CLV** | Cable Laying Vessel |
| **OSV** | Offshore Support Vessel |
| **OCV** | Offshore Construction vessel |
| **AHTS** | Anchor Handling Tug Supply |
| **MCR** | Maximum Continuous Rating |
| **HLP** | Heavy Lift Platform |
| **EIA** | Environmental Impact Assessments |
| **EoL** | End of Life |
| **OWT** | Offshore wind turbine |

# Table of Contents

## List of Figures

## List of Tables

# 1 introduction

In the future, it is estimated that the world's demand for energy will increase by 50% [1]. At the same time, the world will have to tackle the challenges of climate change, meaning new power production must have little impact on the environment.

Development of offshore wind has progressed rapidly in the last decade. In Europe, annual installed capacity has increased from 1 GW per year, to almost 4 GW in 2019, in total tripling offshore wind capacity in Europe in the same time frame [2]. At the same time, the EU and other organisations wish to further grow the offshore wind energy sector. The EU has a goal of 60GW of installed offshore wind energy by 2030. In 2021, the total amount of installed offshore wind power in Europe was 28GW [3].

The rationale behind moving wind turbines offshore is the expectation that winds are more prevalent offshore, and have higher speeds as well. A study of suitable sites for wind power in the north east USA showed offshore sites had 40% higher average wind speeds, compared to onshore sites. Equinor [4] estimates 80% of the world's wind energy resources are at sea.

Another factor for moving wind farms offshore is to better utilise available space. Farms offshore has the advantage of the ability to be located so as not to compete with other primary industries, and, if placed far enough offshore, can avoid disrupting aesthetically pleasing areas, such as on top on mountains, where wind conditions may otherwise be favourable.

However, at some point, these offshore wind turbines reach the end of their lifetime, and will have to be removed. An estimation done by DNV [5] shows that in the next 10-20 years, the number of turbines that reach their expected life time will increase massively, see the graph in Figure 1. What can also be seen from the figure, is that the power capacity increases more sharply than the number of turbines that are being decommissioned.

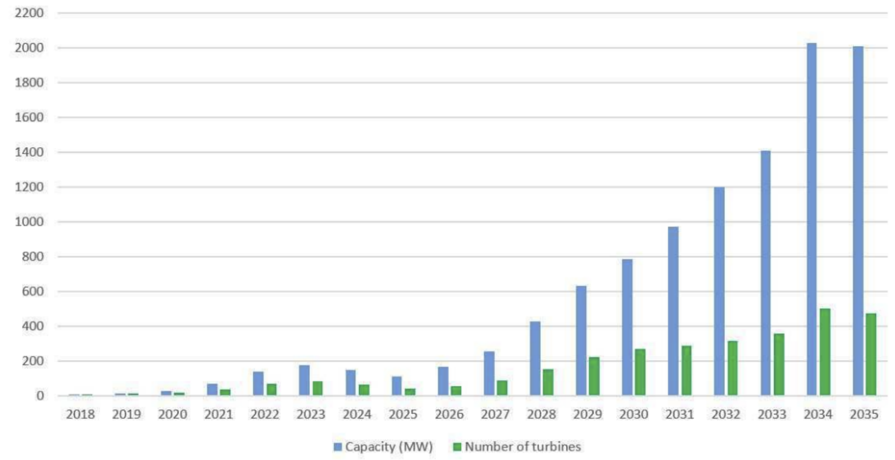

Figure 1: The number of turbines expected to reach the end of their 20 year lifetime per year, and the total power rating of decommissioned turbines. From [5]

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Previous environmental impact assessments and life cycle assessments (LCA) have been conducted on offshore wind farms, although their focus has not been on the emissions from marine operations or the decommissioning process in general. Additionally, the assessments that have been conducted have included smaller turbines and older technology and methods, and not on newer installations, with larger turbines, foundations, and vessels.

The purpose of this thesis is to investigate the greenhouse gas (GHG) emissions, or global warming potential (GWP) of the marine operations conducted when decommissioning an offshore wind farm. The aim of this thesis is to compare the impact on the environment when decommissioning using different methods, and comparing the effect of different types of foundations, wind turbines, and other factors.

# 2 The Offshore Wind Turbine

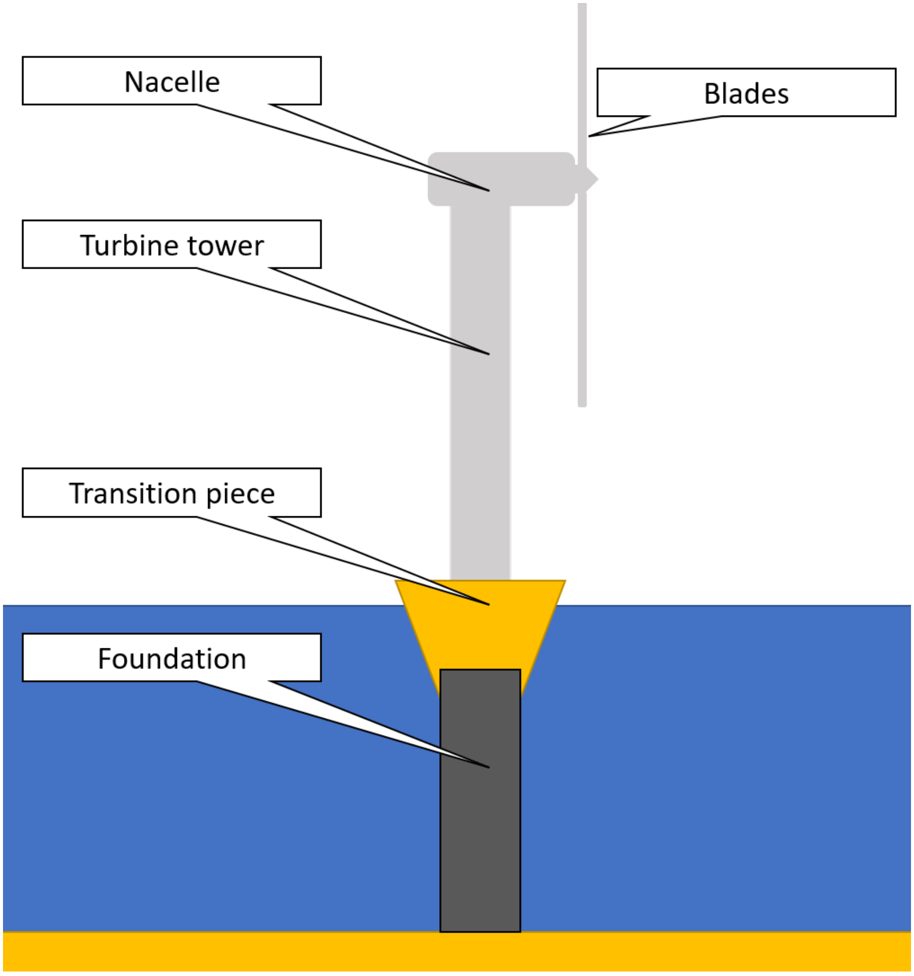


Figure 2: The basic components of the offshore wind turbine.

In the figure above, the main components of an offshore wind turbine generator (WTG) are shown. In the sections below, a quick overview of the the offshore wind turbine will be presented. The turbine pictured is a horizontal-axis wind turbine (HAWT), fastened to a monopile foundation. This is the most commonly found type of offshore wind turbine today, more than 80% of offshore wind installations in Europe have this configuration [2].

## 2.1 The Turbine Blades

The turbine blades are the aerodynamic surfaces that act upon the wind, generating the thrust that turns the generator inside the nacelle. They are made to be as light as possible, often from glass fibres, aluminium, or wood-epoxy composites [6]. The blades need to be able to handle the full aerodynamic load of the winds hitting the offshore wind turbine. The rotor blades also need to be able to regulate their rotation speed as wind speed change. There are two ways of accomplishing this, either by stall-controlled blades or pitch-controlled blades. Stall-controlled blades have typically been used in smaller low power turbines, and do not require control systems in the nacelle [7]. Pitch controlled blades however, require either hydraulic or electric systems for changing the angle of attack of the blades as the wind speed changes [6].

## 2.2 The Nacelle

The nacelle houses the power train and control systems for the turbine. The power train consists of axels for transmitting the rotation of the rotor, often a step up gearbox, and finally the electrical generator. Not all turbines have gearboxes, these are called direct-drive wind turbines. However, most turbines today feature a step-up generator in the nacelle [6].

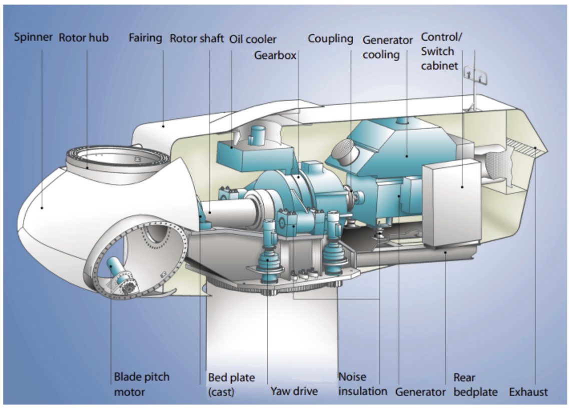


Figure 3: The contents of a typical WTG nacelle. Figure taken from [6].

The nacelle also house the control systems for the turbine. This includes the motors for any pitch controlled blades, as well as the motors for yawing the turbine up to the wind.

As the nacelles and control systems increase in complexity, so do the weight of the nacelle. This will not only increase the required capacity for cranes lifting the nacelle, but will also lead to the tower needing more reinforcement, further increasing weight. This will limit have implications on the operation vessels for offshore wind, and also for transportation vessels.

## 2.3 The Tower

The tower of the turbine is made of steel sheets, rolled into sections of tubing, that are finally welded together into the complete tower [7]. The tower is the largest and heaviest part of the turbine; the towers of the 8MW turbines used in Hornsea Project 2 has a mass of up to 480 Te , and a height of 120 metres [8]. This presents a challenge for decommissioning and installation of the towers, as the vessel will need both crane load capacity and reach to be able to handle the tower.

The inside the tower is typically part of the access system to the turbine, and is hollow to allow maintenance crew access to the nacelle and blades.

## 2.4 The Foundations

From a marine operations perspective, the choice of foundations have the largest impact on the decommissioning procedures and methods of an offshore wind turbine. A description of various types of offshore foundations is presented in this section.

Two main groups of offshore wind foundations exist: floating foundations and fixed foundations. Today, almost all offshore wind is on fixed foundations [2]. Today, fixed foundations is the most common type used for offshore wind farms today, more than 80% of offshore wind turbines have a monopile foundation [9]. The decommissioning procedure of different foundations vary greatly, this is discussed in further detail in Section 6.

Floating wind turbines have not yet been used in large scale commercial wind farms, only pilot projects have been completed so far [10]. However, it is expected that floating offshore wind power will be necessary in order to utilise wind energy resources in areas where fixed foundations are not feasible, such as deep waters further from shore [4, 11]. At the current level of technology, fixed turbines are not feasible at depths greater than 60 metres [10]. Floating foundations are more complex than fixed foundations, as they have to restrict roll, heave, and yaw motions imparted on it by the motions of the sea, and the wind. This greatly increases the complexity of the foundation, including its weight and size [10].

### 2.4.1 Bottom-fixed Platforms

There are three main types of fixed-foundations for offshore wind turbines (OWT). Most of them are monopile foundations, followed by gravity based, and jacket foundations. Sometimes the foundations are divided into five main categories however, in this paper the other two types will be considered variations of the three presented below.

1. Monopile foundations:
   Monopile foundations consist of a steel tube, on which the turbine connects at the top. The pile is driven into the ground, either by a piling hammer, or by creating negative pressure with a pump. The monopile is structure (1) in Figure 4.A similar type of foundation is a tripile structure. This type is also piled into the sea bed, but is constructed with three piles. See Figure 4, no. (5) for an example of a tripile. Monopiles can be used in depths up to 20 m, while tripiles can be used in deeper transitional waters, up to 60 m [10].
2. Gravity-Based foundations:
   Gravity-based foundations (GBF) are heavily ballasted structures that rest on the seafloor, typically made from concrete or steel. The foundation is kept on the ground simply from the weight of the foundation. These kinds of foundation require large amounts of ballast, and their fabrication require large sites suitable for casting the

structure. Gravity-based foundations are used in shallow waters, up to 20 m [10]. A gravity-based foundation can be seen in Figure 4, no. (2). Currently, only 5% of substructures are GBFs, making them the least common type of fixed foundations for offshore wind turbines [9].

3. Jacket structures:
   Jacket structures consist of a frame consisting of three or more legs, with steel beam crossmembers providing rigidity. The structure is usually secured by attaching to piles in the seafloor. Jackets are suitable for depths up to 60 m [10]. See Figure 4 no. (4) for an example of a jacket structure. The tripod is a structure combining elements of the jacket structure and a monopile, see Figure 4, no. (3). About 10% of substructures for offshore wind turbines are jackets [9], however, they are also often used as the foundations for substations. Jackets are required for substations because of their size and weight.

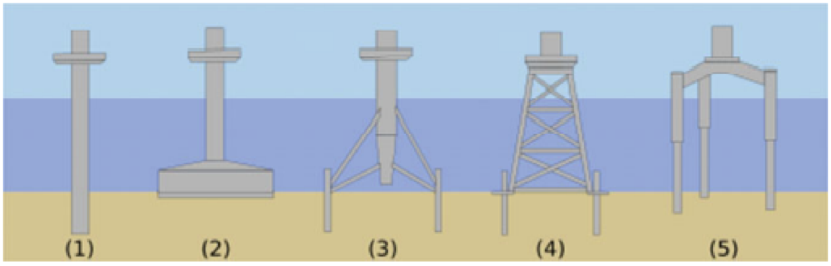


Figure 4: Five different kinds of bottom fixed foundations. The monopiles (1) and jacket foundations (4) are the most common types. Figure taken from *Floating Offshore Wind Farms* by Castro-Santos and Diaz-Casas[10].

### 2.4.2 Floating Platforms

The platforms of floating wind turbines can also be divided into three main categories: these are spar buoys, semi submersibles, and tension leg platforms. As of 2016, only two floating wind turbine field were in operation [2]: Equinor's Hywind Tampen, using their Hywind spar buoy concept [12], and the WindFloat Atlantic project, using a semi-submersible platform [13].

1. Spar buoys (no. 2 in Figure 5):
   Spar platforms are ballast stabilized cylinders, with a low centre of gravity [10]. The fabrication of spar buoys is uncomplicated, and it provides good stability. However, because of the large draft required to sufficiently lower the centre of gravity and to ensure positive buoyancy, transportation and assembly can be complicated. Because of this, spars are typically only suitable for deeper waters. As an example, Equinor's Hywind spar concept has a draft of 78 m [4], obviously making it unsuitable for shallower waters. Because spars are ballast stabilized, they are also heavy. Equinor uses more than 6000 Te of "solid ballast" in their spar [12].

2. Semi-Submersible Platforms (no. 1 in Figure 5):
   Unlike spar platforms, semi-submersible platforms gain their stability by distributing buoyancy in order to have sufficient righting moment. This means the platform can

have a smaller draft than a comparable spar platform. However, the platforms are often large and heavy [10].

3. Tension leg platforms (TLP) (no. 3 in Figure 5):
   Tension leg platforms can be characterized by the fact that they are positively buoyant (including the weight of the tower and turbine). The platform is ”held down” by the mooring lines. This also ensures stability. A disadvantage is that the platform is vulnerable if an anchor line, or anchor, suffers a failure. This could potentially result in a loss of stability.

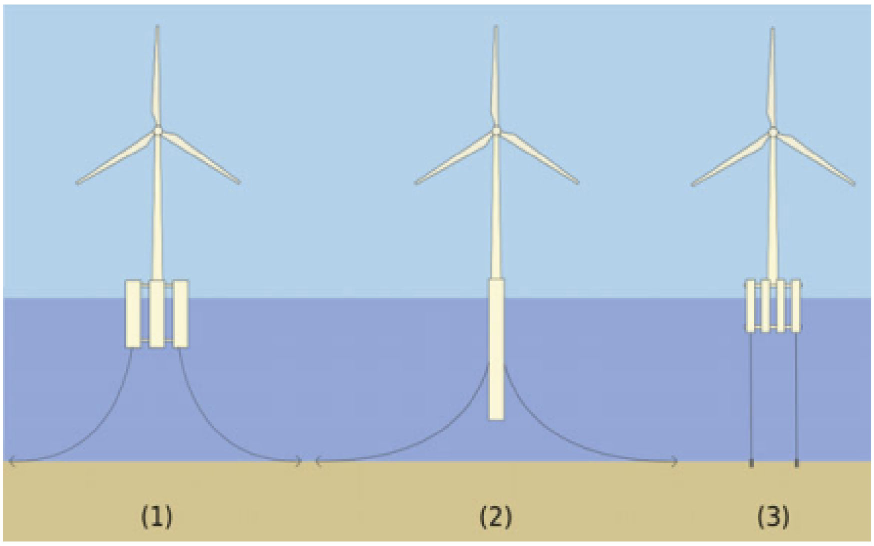


Figure 5: Three types of floating wind turbine foundations. Note the tension caused by the buoyancy of the TLP (3). Figure taken from *Floating Offshore Wind Farms* by Castro-Santos and Diaz-Casas[10].

### 2.4.3 The Transition Piece

The transition piece is used for monopile foundations. It is the interface between the turbine tower and the foundation. Since the process of installing a monopile requires a hammering action, having the interface be part of the foundation would mean it would get in the way of the installation hammer. For other types of foundations, the ”transition piece” is already a part of the structure.

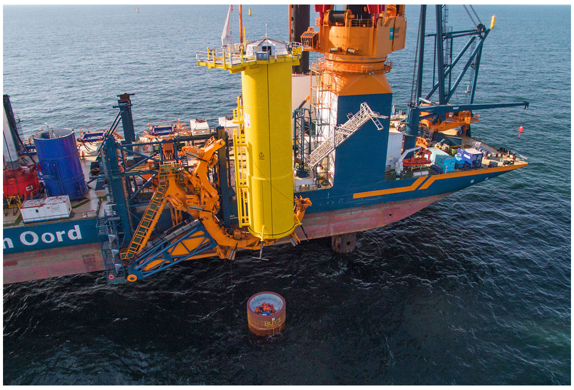


Figure 6: The installation of a transition piece on a monopile.

Source: From [14]

# 3 The Offshore Wind Farm

An offshore wind farm is collection of electrically interconnected wind turbines [15] . The wind farms systems include components for transmitting power to shore, and internally between turbines and substations in the offshore wind farm. The different power transmission components are presented below.

## 3.1 Substations

The offshore substation transforms the voltage of the electricity produced by the wind farm to a higher voltage to minimize transfer losses through the export cable to the power grid [16]. Substations are large and heavy, the substations for the Hornsea 2 project weigh up to 8000 tonnes and measure 80m x 65m x 35 m [8]. This makes them more similar to topsides of platforms used in oil and gas, than to offshore wind turbines [5]. Consequently, their foundations are also larger and heavier.

## 3.2 Power Transmission Cables

The cables on an offshore wind farm are divided into two subgroups: inter array cables, and export cables.

- Inter array cables:
  Inter array cables connect the WTGs to the substation. Several WTGs often share the same cable connection to the substation, in order to minimize the amount of cabling necessary. They are typically buried 1-2 metres below the mud line [16].
- Export cables:
  Export cables run the converted electricity from the substation, and connects with the power grid. High voltage cables, capable of transmitting more than 100 kV are used. For this assessment, it was assumed that export cables have a weight of 100 kg/m, which will be used to determine capacity of vessels involved with cable removal, see Section 9.2.4 [16].

# 4 Emissions from offshore wind

Although the conversion of wind to electricity does not produce greenhouse gases, the construction, maintenance, installation, and as is the focus of this thesis, the decommissioning of the wind turbines are all processes that are sources of emissions. In this section, a short overview of where emissions from offshore wind come from will be presented.

Emissions from offshore wind is generally considered to be larger than for equivalent onshore wind, and some LCAs show that offshore wind power can have more than twice the global warming potential (GWP) compared to its onshore counterpart [17]. In Europe, that means 23% of wind power related emissions came from offshore wind, while only 12% of wind power is produced offshore [3].

The global warming potential is not the only type of environmental impact caused by an offshore wind installation. Waste production, disturbance of marine and land ecosystems, acidification, land and resource use are all impacted by offshore wind. These types of environmental impacts will not be part of the assessment done in this thesis, however. As mentioned in Section 1, the global warming potential, or the greenhouse gases emissions will be the focus of this thesis.

## 4.1 Manufacture

A fully functional offshore wind installation consists of two main components: the foundation, and the wind turbine generator (WTG). in some LCAs, the manufacture of these components accounts for more than half of total life cycle emissions [18, 19]. In these assessments, this included material extraction, processing and final manufacture. The most GWP intensive part of this stage is the extraction and processing of raw materials.

The offshore wind industry is developing quickly, and it is expected that techniques and technologies for offshore wind power will be improved, making the manufacture of offshore wind turbines more streamlined and efficient [20]. However, the effect this has on reduction of GWP may be limited, as some estimate only 5% of total GWP-contribution comes from the final fabrication of materials into WTG and foundation components [21].

### 4.1.1 The Materials

The WTG consists of the tower, nacelle, and turbine blades. The tower is almost always constructed from steel sheets, rolled into sections of tubing that are finally welded together into a turbine tower [7]. The mass of the tower is dependent on the turbine's size, rating, required weather resistance or other factors. A typical WTG will have a tower mass of 200-500 Te. In addition, nacelle and turbine blades are made from a variety of materials, including various polymers, composites, and for the nacelle, various electronic components, and lubrication oils. A search in the Ecoinvent [22] database reveals the following GWPs for a selection of typical WTG construction materials.

Table 1: GWP of WTG construction materials.

| **Material** | **GWP** kgCO$_2$-eq/kg |
|---|---|
| Reinforced steel | 3.8 |
| PVC | 2.26 |
| Lubricating oil | 1.45 |
| Aluminium | 20 |

As mentioned before, a typical WTG weighs several hundred tonnes. Given the data in Table 1, a WTG will have a GWP of several times its own mass in CO$_2$-equivalents, only from the production of the materials used in the wind turbine.

### 4.2 Transportation and Vessel Operations

During the installation phase, emissions stem from the power production for installation and transportation vessels. Transportation of goods is one of the main contributors to global warming worldwide [1], and for the installation of an offshore wind farm several tonnes of equipment, tools, and components have to be transported on shore to the port, and at sea by boat.

An estimation by Reimers et al. [18] found that about 20% of total emissions from offshore wind turbines were related to vessel use and maritime operations. This included all parts of the life cycle: installation, operation, and decommissioning. The pollution from vessels come from production of energy in marine engines, typically diesel electric generators in the vessels used in offshore wind. The combustion of diesel oil produces greenhouse gases, the most important of which is CO$_2$, or carbon dioxide.

## 5 Regulations

Currently, there are few regulations concerning offshore wind decommissioning, and there is a lack of guidelines for recommended practices [23]. Most regulations regarding the removal and decommissioning of offshore structures today is based on the OSPAR and and UNCLOS conventions [24]. These documents establish the general guidelines for all decommissioning activities at sea. The UNCLOS convention states that " *Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent international organization. Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States.* [25], establishing that once removed, subsea structures should not inhibit economic activities or the disturb marine environment.

The IMO guidelines on removal of of offshore installations and structures further specifies guidelines for removal of offshore installations [26]:

- 3.2: "All abandoned or disused installations or structures emplaced on the sea-bed on or after 1 January 1998, standing in less than 100 m of water and weighing less than 4,000 tonnes in air, excluding the deck and superstructure, should be entirely removed."

- 3.3: "Removal should be performed in such a way as to cause no significant adverse effects upon navigation or the marine environment."
- 3.5 "Notwithstanding the requirements of paragraphs 3.1 and 3.2, where entire removal is not technically feasible or would involve extreme cost, or an unacceptable risk to personnel or the marine environment, the coastal State may determine that it need not be entirely removed."

Since most installations and structures related to an offshore wind farm has a weight of less than 4000 tonnes, and often are often installed in depths of less than 100 metres, article 3.2 of the IMO regulation implies that all offshore wind structures should be entirely removed. However, in practice the exceptions from article 3.5 are applied. Partial removal of installations and structures is almost exclusively the method chosen by operators [27, 28].

# 6 Decommissioning Operations

The decommissioning or disassembly of individual wind turbines in an offshore wind farm is for the most part the reverse of the installation process [15, 29]. Because of this similarity, many assumptions and data are based on installation statistics, which is much more available compared to statistics on decommissioning, as only a handful of offshore wind farms have reached the end of their life cycle [23]. In this section, an overview of decommissioning methods will be presented.

## 6.1 Removal of Foundations

Different foundations vary greatly in the way they are removed. Their differences in size, function and mass all impact how the different foundations are removed from the seabed.

- Floating Platforms

  In the same way floating wind turbines are assembled [12], decommissioning of floating wind turbines will involve towing the fully assembled wind turbine and foundation back to a yard for disassembly. This is the method described in the decommissioning programme for Equinor's Hywind Tampen pilot project [30]. However, Equinor has explored alternative methods for installation of offshore wind, some of which include assembly of the floating wind turbine offshore [31]. It is possible that disassembly of the tower at shore would then also be possible.
- Gravity-Based Foundations

  Gravity based foundations are rarely used for offshore wind purposes. In 2020, no offshore wind installation were installed with GBFs [9]. Consequently, little research has been done into different decommissioning methods for GBFs. When the Vindeby offshore wind farm was decommissioned, the chosen method involved breaking the foundations up using excavation equipment [32]. However, this is unlikely to be the chosen method for newer wind farms in deeper waters further offshore. The decommissioning programme for the Gwynt y Môr offshore wind farm proposes lifting the GBFs off the seabed in one piece using a heavy lift vessel (HLV) [33]. The GBFs will be transported back to shore using specialized barges.

- Monopiles

  There are two main methods of removing monopile foundations: either by complete removal, or by partial removal, cutting the pile below the sea floor.

  Completely removing the piles is not commonly used in offshore wind decommissioning, but may be a better option in order to minimize environmental impacts [28]. Several methods for the complete removal monopiles exist, such as by vibration hammer, dredging, pressurized air removal, or buoyancy. These technologies are largely untested, and have not been used widely offshore [28].

  The partial removal of monopiles is how all offshore wind farms have been decommissioned so far. This involves by dredging the sea floor 1-2 metres below the mudline around the monopile, and then cutting it [28, 8, 34]. The piles are typically cut by from the outside with a pressure jet cutter or with a diamond wire [28]. Using explosives is also an option, but it is not typical [35]. Figure 7 shows the cutting and partial removal of a monopile.

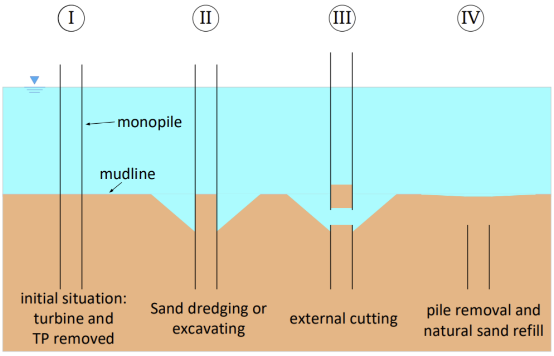


Figure 7: The cutting and partial removal of a monopile.

  In the assessment conducted in this thesis, only partial removal by cutting will be considered.

  Before the monopile can be removed however, the transition piece is typically removed first. The transition piece can often be simply unbolted, and lifted on to a suitable transportation vessel [8].

  The monopile removal is typically conducted by a jack up vessel. The piles and transition piece is most often transported back on a transportation barge [15].

- Jacket Foundation

  The removal of jacket foundations is similar to removal of monopiles. The piles at the corners of the jacket need to be removed before the jacket can be lifted off the sea floor. These piles can be removed either partially or completely, however, in many decommissioning plans, the piles are only partially removed [8, 36, 34, 37]. After the piles are cut, a heavy lift vehicle is used to lift the jacket structure onto a transportation vehicle.

## 6.2 Disassembly of the Turbine

The disassembly of the turbine is the reverse of the installation. There are numerous ways of installing a turbine, and consequently an equal number of ways to disassemble a turbine. In Figure 8, different options for wind turbine installations are shown.

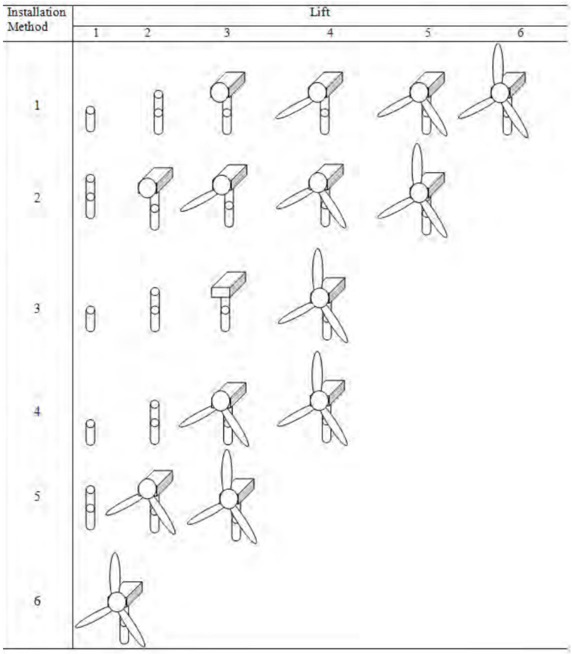


Figure 8: Different options for wind turbine installation. The columns are the numbers of lifts required for chosen methods (rows). Taken from [16]

The figure above shows different options for the assembly of the tower, rotor blades and the nacelle. For instance, option number 1, 3, and 4, shows how the tower can be installed in two parts, and the figure also shows how blades can be transported and installed with the nacelle, or separately.

In a report by the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), later reorganized into the Bureau of Ocean Energy Management [16], the effect of the different installation methods on installation time were explored. They found that methods 3-6 took longer time than methods 1 and 2. However, the report concluded that this was an unlikely result, and commented that the sample size was too small to draw a meaningful conclusion. This study was conducted to establish the feasibility of offshore wind farms in American waters. In the assessment conducted in this thesis, the effects of different turbine installation options will not be considered.

Typically, a jack up vessel is used for dismantling the turbine, and to transport components back to shore [15, 16].

## 6.3 Cables

Cables can either be removed completely, or partially. Partial removal of cables includes only removing parts of the cables that are exposed. Cables are not covered by the OSPAR regulations, and can be left in situ if they do not disturb other users of the sea [38].

Cable removal is done by a vessel similar to the vessel used for installing the cables, a cable laying vessel (CLV) or a cable repair vessel.

### 6.4 Substations

The substation top pieces are often large heavy constructions that require HLV to remove [16]. This operation is similar to the removal of topsides of oil platforms [5]. The substation is lifted off the foundation in one piece, and then transported back to shore for further disassembly on a specialized barge. The foundations of a substation are Decommissioned in a similar fashion to the WTG foundations, although they may be slightly larger in size [34, 37].

## 7 Life Cycle Analysis

Even though the environmental impact analysis conducted in this thesis will not consider the entire life cycle of an offshore wind farm, the methodology and phases defined in the ISO14040 and ISO 14044 standards will be used as a basis for the assessment conducted in this thesis. The advantage of this is that this enable the comparisons of the results of this assessments with other full life cycle LCAs.

### 7.1 Use of LCA

As mentioned earlier, producing sustainable and low carbon solutions is becoming increasingly important in order to meet the goal of increasing energy production, while at the same time reducing the impact on the environment. Traditionally these demands have been the requirement of governments, requiring industry to purchase quotas for $CO_2$ emissions. One example is the EU's emissions trading system (EU ETS), where current prices are over 80€ per tonne $CO_2$ [39]. However, lately private institutions such as equity funds, investment bankers, and loaners have set their own requirements for a project's sustainability, in order to receive funding [40]. Consumers are also becoming increasingly aware of climate challenges. Thus, for a project pitch to be successful, the project owners should provide a estimate of their projects climate footprint.

Bonou et al. [21] provide examples for how LCAs can be used in decision making internally within Siemens. Choice of materials, supply chain management, and optimizing logistics are the key areas of focus, where LCAs can be used as a decision-making aid.

### 7.2 ISO 14040 & 14044

The international Organization for Standardization (ISO) have produced the ISO 14040 and ISO 14044 standards as a guide for conducting an LCA [41] [42]. The ISO 14040 presents the guiding principles for the LCA process, while the ISO 14044 standard specifies further requirements for the individual phases of the LCA. The goal of the standards is to harmonize the contents of different LCAs, so their findings and results can be compared. The goal of the standards is not to force all LCAs to follow a specific methodology.

The ISO standards divide the LCA process into four stages:

- Goal and scope definition
- Inventory analysis

- Impact assessment
- Interpretation

The stages facilitate an iterative process, where the result from one stage influence the previous stages. The reasoning being that knowledge of the system being considered increases while doing the LCA, leading to better assumptions and overview of what factors and processes are important to include within the system boundary.

The stages and iterative process of an LCA are shown in Figure 9.

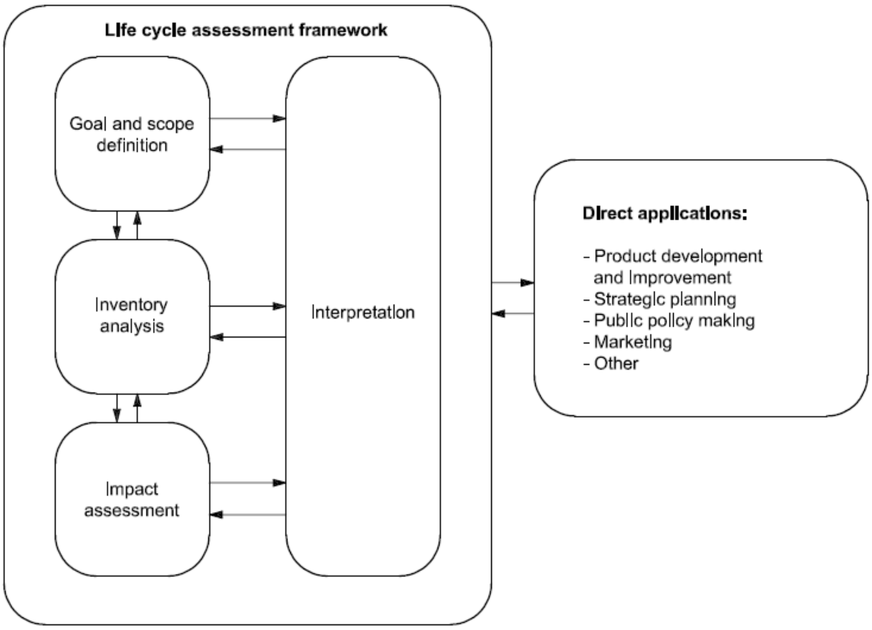


Figure 9: The stages of an LCA, according to ISO14040 [41]

## 7.3 Phases of an LCA

### 7.3.1 Goal and Scope Definition

The first stage of an LCA is the goal and scope definition. The ISO standard emphasizes that the scope of an LCA depends on the goal of the LCA. Some LCAs, such as Bonou's analysis of gearing systems [21], may only focus on specific components of a product, while others put emphasis on a larger perspective for analysis. Kannen [43] has published a paper on the need for an "integrated assessment" of new large scale offshore wind. In his paper, this includes analyses of both environmental and economic factors. According to the standard, economic analyses are not part of an LCA, however, it does encourage applying other life cycle studies, such as life cycle costs (LCC). The LCA itself only considers aspects of natural environment, human health, and resource use.

Because of the iterative nature of an LCA, the scope may be refined further during the duration of the study [42]. ISO 14044 notes four aspects of the study that must be "unambiguously" stated when defining the goal of a study. The standard defines the function of the product as the defining property of the system being studied.

- The intended application
- The reasons for carrying out the study
- The intended audience
- Whether the results are intended to be used comparatively

Definition of the goal and scope also include defining the *functional unit.* The functional unit is intended to provide a reference for the inputs and outputs of the product being studied. For an OWT, a sensible functional unit may be the energy produced e.g. MWh. The inputs and outputs of the life cycle inventory analysis (LCI) and life cycle impact assessment (LCIA) should then all be related to this unit. The functional unit decides what metric is being studied in the LCA, and is essential to the goal and scope definition phase. The system boundary is also decided during this phase. The system boundary defines what *unit processes* should be included in the LCA. The unit processes are smallest processes considered in the life cycle inventory analysis (LCI). More on the LCI in Section 7.3.2. The processes and input and output flows included within the system boundary is part of the system environment, see Figure 10. The flows are divided into product and elementary flows. The product flows are produced by this system, or other systems. The elementary flows include resource use and emissions.

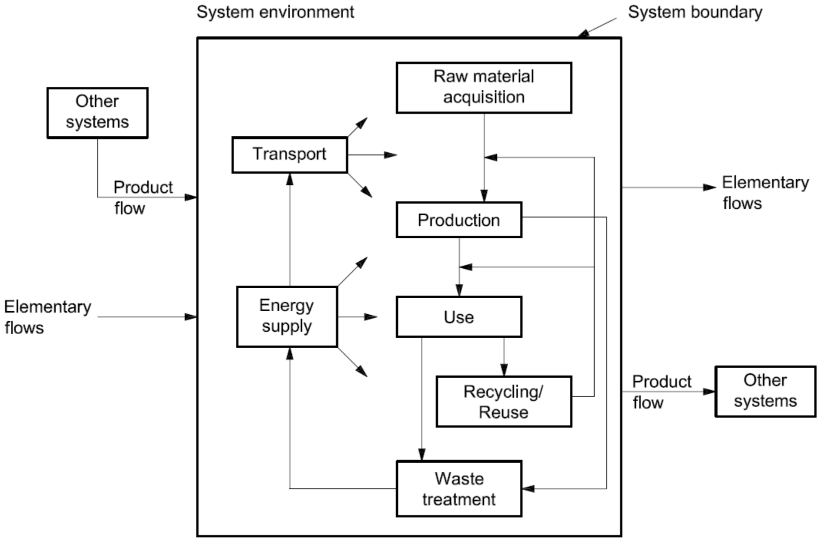


Figure 10: The system environment, as defined in ISO14040. The elementary flows include raw material inputs, and emissions. The figure also shows product flows to and from other systems.

Any assumptions made must also be made clear when defining the scope of the study, as well as requirements for the data quality. The purpose of the goal and scope phase is to ensure transparency, and to make any biases clear.

### 7.3.2 Life Cycle Inventory Analysis

The life cycle inventory analysis (LCI) is the second phase. The initial plan for the LCI is provided by the goal and scope definition from the first phase. The primary goal of the

LCI is to collect data and establish calculation procedures for the impact categories in the next phase [41]. See Figure 11 for an overview of the stages in an LCI.

Data is collected for every unit process under consideration. The data can be energy inputs, raw material inputs, emissions, and waste. The calculation step involves relating data to the unit process, and to the functional unit. Validation of the data collected should also be conducted during this stage. Validation of the data should confirm that the quality of the data is sufficient for the intended depth and breadth, as established in the goal and scope definition [42].

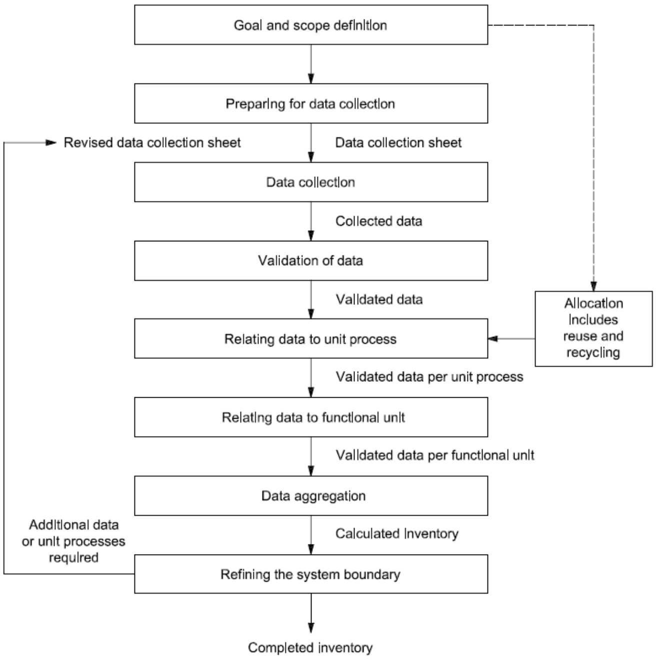


Figure 11: A simplified overview of the LCI process. Notice the arrows indicating the flow of the iterative process. Figure taken from the ISO 14044 standard [42].

The results from the LCI is the data collected and the calculations validating the results and relating them to the functional unit. This importantly includes the elementary flows: environmental emissions and resource use.

### 7.3.3 Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) is the penultimate phase of a complete LCA analysis. The results from the LCI is used to evaluate the environmental impact from the processes considered. The LCI data is associated with environmental impact categories and category indicators [41]. An example of an impact category can be climate change, while the category indicator can be kilogrammes of $CO_2$-equivalents. ISO 14044 [42] specifies requirements for choosing impact categories and category indicators.

### 7.3.4 Interpretation

The final stage of the LCA is the interpretation of the results from the previous stages. The ISO standards [41, 42] emphasize that uncertainties from the results, particularly from the LCI, and applications of the LCA should be the focus of the interpretation.

## 7.4 LCA Methods

When the environmental impacts from the LCI are assessed in the LCIA, the calculation and the selection of the impact categories and category indicators depend on the goal of the study. As such, different methods for assessing the environmental impacts have been developed. ISO 14044 [42] further specifies that these methods should be "internationally accepted" and based on "international agreement". Multiple intergovernmental organisations have developed their own models for evaluating environmental impacts. LCAs on offshore wind have used several different methods. Weinzettel et al. [19] used a method developed the university in Leiden, the CML baseline method. Reimers et al. [18] used a specification developed by the Intergovernmental Panel on Climate Change (IPCC), while Bonou et al. [21]used the ReCiPe method developed by NTNU in collaboration with other universities and research institutes [44].

The ReCiPe and CML methods are both continuations of the specifications established by the IPCC, meaning they meet the recommendations from the standards. [44, 45].

## 7.5 LCA Databases

Collection of data for the LCI can be very labour intensive. Therefore, several databases have been collected. One example is the EcoInvent database, which is used by several authors in the literature [18, 19, 21]. The EcoInvent database is maintained by the EcoInvent foundation [22]. Other databases are available, such as the EU & DK Input Output database which is mainly developed for products commonly imported in to the EU, and the CEDA database developed by the Vital-Metrics group [46].

## 7.6 LCA Software: SimaPro

SimaPro is a software made for conducting life cycle assessments. It is developed and maintained by PRé sustainability [47], who also developed the ReCiPe methodology. The SimaPro software is developed to follow the phases and requirements established by the ISO14044 & 14040 standards. See Figure 12 to see the LCA phases as presented in SimaPro.

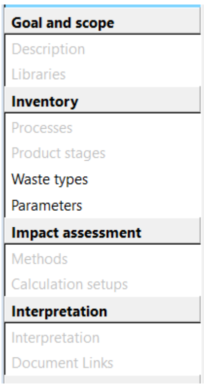


Figure 12: Screenshot of the main menu in SimaPro. Note how the headers concur with the phases from the ISO14040 standard.

SimaPro includes tools for automatically importing environmental data from various databases, as well as calculation methods. The software allows for defining custom processes, and combining them with pre-existing data from the databases.

# 8 Establishment of the Goal, Scope & Boundaries

In this section, the goal, scope, and boundaries of the environmental impact assessment will be established, as described in Section 7.

## 8.1 Goal and Scope Definition

The goal of this study is to analyse and compare the environmental impact from the decommissioning of varying offshore wind farms. To achieve this goal, several offshore wind farm decommissioning cases will be established, including a base case representing a typical or average wind farm. These wind farm cases will primarily be based on newer, modern offshore wind farms built in the last decade, and will be decommissioned using modern techniques. In each case, individual parameters of the wind farms will be adjusted, which will allow for effective comparisons. Data on different decommissioning methods will also be collected.

The different parameters of an offshore wind farm that will be analysed in this assessment are the following:

- Distance from shore
- Number of turbines to be disassembled
- Size of the turbines
- The type of foundations to be removed
- The vessels involved in the decommissioning operations
- The amount of export cables to be removed.
- The substations to be removed, and their foundations

## 8.2 The Functional Unit

The purpose of the functional unit is, as mentioned in Section 7, to act as a reference in order to normalise results assessments. It also provides a reference between input and output for the system. The functional unit must, in this case, be able to accurately represent outputs from a wide variety of offshore wind farms, despite differences in the scale and methods of the decommissioning activities. A suitable functional unit for an electricity producing offshore wind farm will therefore be one mega-watt hour [MWh] of rated power production over the life span of the offshore wind farm, not adjusted for transmission losses, wind conditions, or other factors. This will ensure comparisons are possible despite differences between the wind farm cases that were established in Section 9.

## 8.3 System Boundary

The system boundaries are shown in Figure 13

Figure 13: The system boundary: Use of ROV-vessels to prepare decom. operations, the disassembly of WTGs, the removal of foundations, recovery of cables, and transportation back to shore.

Source: Images taken from [48, 49, 50, 51, 52]

The system includes the energy use by vessels related to the decommissioning operations, such as the disassembly of turbines, preparation of the seabed before the removal of foundations, the demolishing or removal of the foundations, the removal of substations, and the transportation of all materials and components back to shore. All activities associated with the operations are also included, such as a reasonable time waiting on weather (WoW), and preparing for operations to commence.

The system does not include the use of capital infrastructure is not included, nor is expected or regular maintenance on equipment as a result of its use in the operations. Waste management and recycling of materials used for the wind farm is not within the scope of this assessment either.

## 8.4 Allocation Procedures

For the assessment in this thesis, it would have been possible to allocate the energy used by vessels when traveling between worksites. However, this will not be done in this thesis, as it would have made comparing results more difficult.

#### 8.4.1 LCIA Methodology and Types of Impact

### 8.5 Impact Categories

In order to fulfil the goals and intended purposes of the assessment as stated above, suitable impact categories should be chosen. There is no standard impact category defined in the ISO standard, so the impact category should be chosen based on what comparative analysis should be performed on the assessment.

For this assessment, the global warming potential was chosen as the impact category. GWP is a way of representing the environmental impact of released greenhouse gases in a way that normalises different greenhouse gases contribution to global warming. The normalisation is based on one kilogramme of $CO_2$ gas released in to the atmosphere, or kg $CO_2$-eq. Table 2 shows the $CO_2$-eq. of common greenhouse gases. The GWPs in the table are taken from IPCC's list of global warming potentials for 100 years [53]. This method will be used to calculate the GWP in this thesis.

Table 2: The global warming potential of common greenhouse gases.

| Gas | Chemical Formula | Global warming Potential factor |
|---|---|---|
| Carbon Dioxide | $CO_2$ | 1 |
| Methane | $CH_4$ | 28 |
| Nitrous Oxide | $N_2O$ | 265 |
| CFC-11 | $CCl_3F$ | 4660 |

As mentioned in the introduction, much effort is being put on reducing the carbon footprint of energy production. Therefore, choosing global warming potential as an impact category was a natural choice. The study of GWP of offshore wind farms have also been done in the past by several authors [18, 19, 21], and the selection of this impact category will will allow for comparisons with their results.

### 8.6 Data Requirements

The data collected for use in this analysis should be as up-to-date as possible, preferably including assumptions regarding conditions in the near future. As offshore wind farm decommissioning is a new field of study, real world data is hard to obtain, and generally the quality of data available is generally low. In this thesis, a substantial amount of data is based on statistics from installation of offshore wind farms. However, as mentioned in Section 6, decommissioning share many characteristics of installation, making the use of installation statistics also suitable for the scope of this assessment.

The emissions data used in this assessment was collected using NTNU's access to the Ecoinvent 3 database [22], through the SIMApro software.

## 9 Inventory Collection

The inventory analysis involves collecting data, and performing calculations on the data in order to quantify the inputs and outputs of the product system. Inputs can include energy, raw materials, other products, while outputs can include waste, emissions to water and air, and any bi-products.

The data was collected from mainly two types of sources:

- Statistics on Installation:
  As there are few offshore wind farms that have been decommissioned, and the ones that have been decommissioned were small scale pilot programmes, statistics on installation of wind farms have been used as a supplement to predict the duration and scope of the decommissioning operations. As mentioned in Section 6, the decommissioning process is often very similar to the installation procedures.
- Future Plans for Decommissioning:
  Operators that are granted licenses for offshore wind development in the UK are required to present plans for the decommissioning of the site [24]. These plans often describe what methods are expected to be used for the decommissioning, and sometimes also the expected duration of the decommissioning. They also specify what types of vessels that are necessary to perform the decommissioning.

The inventory analysis has been used to develop a basecase wind farm, as well as several other wind farm cases, in order to facilitate comparisons.

## 9.1 Vessel Data

A short analysis of decommissioning programmes show what vessels are needed to complete the disassembly of an offshore wind farm. The results are presented below, in Table 3. There are differences in the level of detail between the plans, and not all plans describe all phases of the decommissioning. The consequence is that what vessels are expected to be necessary for the decommissioning is not always specified.

Table 3: Plans for monopiles in decommissioning plans

**Vessel required for each part of the decommissioning**

| **Wind Farm** | **WTG** | **Foundations** | **Cables** | **Substations** |
|---|---|---|---|---|
| Sheringham Shoal [54] | SPIV | SPIVs, ROV-vessel and Barge+AHTS | No planned cable removal | HLV and AHTS |
| Doggerbank A & B [34] | SPIV | SPIV and barge/ AHTS | Not specified | HLV and AHTS |
| Doggerbank C [37] | SPIV | SPIV and barge/AHTS | Not specified | HLV and AHTS |
| Gwynt y Môr [33] | SPIV | SPIV or HLV and barge + AHTS | CLV | SPIV or HLV and barge + AHTS |
| Hornsea Project 2 [8] | SPIV | SPIV and ROV-vessel | CLV | HLV and barge+AHTS |
| Dudgeon [36] | SPIV | SPIV | No planned cable removal | Not specified |

Jack up vessels, and preferably self propelled installation vessels (SPIV) are the most common vessel found in the decommissioning plans, sometimes used for all components of the wind farm, apart from any cable removal. Most of the plans specify that the SPIVs used when the wind farm has reached its end of life are expected to be high capacity vessels. Therefore such vessels were focused on in this assessment.

Some of the plans also include using ROV survey vessels before removing the foundations, however, it was assumed in this assessment that all farms will require this.

The emissions from the vessels' energy use was modelled using Ecoinvent's diesel-electric generating set [22]. The vessels energy use was found using available consumption data from the Seaweb database [55], as well as an assumed specific consumption of 180g/kWh for a typical marine diesel engine [56].

The different vessels will be discussed in greater detail in the following sections.

### 9.1.1 Jack Ups

As mentioned in Section 6, jack up vessels are typically used in the installation and decommissioning of offshore wind. Almost always for the turbines, but often for the foundations and piles if their weight and size allows it. Typical installation jack up vessels are shown below, in Table 4.

Table 4: Installation vessels, their capacities and their energy demand when traveling at service speed.

| **Vessel** | **Type** | **Energy demand** [MW] | **Capacity** |
|---|---|---|---|
| Bold Tern [57] | SPIV | 8.1* | 9000t - 3600m2 |
| Brave Tern [58] | SPIV | 8.5* | 9500t - 3200m2 |
| MPI Adventure [59] | SPIV | 6.6* | DW = 6000t |
| Innovation [60] | SPIV | 12.8* | 8000t - 3400$m^2$ |
| Sea Installer [61] | SPIV | 8.5* | 6000t - 3350m2 |
| Sea Challenger [62] | SPIV | 8.5* | 6000t - 3350m2 |
| MPI Resolution [63] | SPIV | 4.3 | 5000t - 3200$\text{m}^2$ |
| Average | - | 8.2 | - |

*estimated based on available consumption data from *MPI Resolution* [55]

The vessels presented above are all larger jack up SPIVs, which are most commonly used in offshore wind today [15]. They have deck load capacities between 6000 and 9000 tonnes, and a free deck area of 3000-3500$\text{m}^2$. According to Bold Tern's specification sheet [57], vessel has capacity to transport and install 3, 12 MW turbines, 4, 10 MW turbines, or 8, 3-4 MW turbines. Since all the in the list above have similar weight capacities and deck areas similar to the *Bold Tern*, it was assumed in this thesis that any jack up SPIVs involved will have capacities identical to the *Bold Tern.*

The turbine storage capacity of the installation vessels was expected to have a significant impact on the results, as it will dictate the time the vessel can be at sea. When the vessel is fully loaded with turbines or foundations, it will have to return to port, increasing both the time it takes to disassemble the wind farm, and the energy needed for travel back-and-forth to the wind farm.

The vessel *MPI Resolution* has publicly available consumption data for fuel, at 18.5 tonnes of fuel per day at cruising speed [55]. This was used as a basis for calculating energy demand for the other installation vessels in the table above. The fuel consumption was extrapolated based on the installed MCR of the other vessels in the table above, and an average value was found. See appendix H for the full calculations.

Some jack up vessels are not equipped with their own propulsion systems, but will still have to produce power using diesel generators to operate cranes, jack up systems, and habitation modules, similar to the SPIVs presented in the section above. Examples of such vessels are the *Excalibur* and the *Wind Server.* Such vessels will not be considered in this assessment. However, if such vessels were to be included, it was assumed they would not change the result in any meaningful way, as they would still require tugs and powerplants with similar energy needs as a SPIV.

### 9.1.2 Barges and Tugs

As shown in Table 3, several wind farm operators plan on using transport barges to transport foundations. This may be because the operator expects a jack up vessel will not have the capacity to store the foundations on board, as monopile often weighs more than the turbine. Free deck space can also be an issue, as the monopile foundation also consist of an transition piece that has to be removed and stored separately. Another reason may be a desire to reduce backloading trips for the jack up vessel.

In addition, tugs and anchor handlers may be required for other parts of the decommissioning, such as for towing heavy lift platforms for the substations, and as is the case for floating wind turbines, for the tow back of the wind turbine back to the yard, as well as for the removal and transportation of the anchor lines for the floating platform. When tugs are needed for operations, it was assumed that they are required to remain at sea for the same duration as the vessels they are assisting.

The transport barges will require a tug to transport the foundations back to port. it was assumed that anchor handling tug supply vessels (AHTS) will be used as tugs. In the table below, a number of such vessels are presented. Some, such as the *Normand Sapphire* have been involved in offshore wind installation.

Table 5: AHTSs and energy demand when traveling.

| **Vessel** | **Type** | **Energy demand** [MW] | **Capacity** |
|---|---|---|---|
| Normand Sapphire | AHTS | 4.5 | 282 |
| Far Sabre | AHTS | 5.86 | 187 |
| Sea Tiger | AHTS | 8.10 | 180 |
| Bear | AHTS | 11040 | 7.41 |
| Gerard Jordan | AHTS | 6.71 | 163 |
| Atlantic Brigand | AHTS | 7.87 | 150 |
| Average | - | **7.39** | - |

The energy consumption data of the AHTS' are based on available data from the Seaweb database [55]. Their energy demands are similar to SPIVs with similar MCRs, as expected. However, these vessels will probably spend more time in a DP condition, as they do not have the jacking capabilities of jack up vessels.

Alternatively, the modelling of transportation by barge could have been done using Ecoinvent's built in model for barge transportation. However, this model is based on a tonne-kilometre calculation, which could not have taken into account the time the transportation barge is waiting for the SPIVs or other vessels to compete their operations.

### 9.1.3 ROVs Operation Vessels / OSVs

Vessels carrying Work ROVs are needed for some parts of the decommissioning process, particularly in connection with cutting cables and digging away scour protection before removing foundations. Most SPIVs presented in the sections above do not appear to be carrying their own work ROVs [57, 59], so vessels with ROV handling and launching capabilities will be needed. Such vessels can be AHTSs, or more typically, offshore support vessels (OSV).

Table 6: OSVs and energy demand when traveling.

| **Vessel** | **Type** | **Energy demand** [MW] |
|---|---|---|
| Normand Sapphire | AHTS | 4.5 |
| Dina Star | OSV | 4.9 |
| Edda Flora | RSV | 6.7 |
| Normand Ocean | OSV | 5.0 |
| Onyx | OSV | 7.87 |
| Maersk Nomad | OSV | 7.9 |
| Island Performer | OSV | 7.9 |
| Ariadne | OSV | 7.9 |
| Normand Jarl | OSV | 7.3 |
| Deep Cygnus | OSV | 7.2 |
| Normand Mermaid | OSV | 6.9 |
| Edda Fauna | OSV | 6.9 |
| Average | - | 6.3 |

Source: Data from Seaweb [55]

The average energy consumption of these vessels are slightly lower than than for the AHTS' and SPIVs. In addition, they are not used as frequently as other vessels. Their impact is therefore expected to be smaller than for other vessel types.

### 9.1.4 Cable Laying/Repair Vessels

Although many operators plan to let cables remain in situ after decommissioning, see Section 9.2.4, this is not possible if some parts of the cable are exposed. These parts of the cable will need removal by a cable laying or repair vessel (CLVs).

CLVs can mostly be split into two different groups: large cable laying vessels, used for laying the hundreds of kilometres of high voltage export cables, and smaller cable repair vessels. In this thesis, it was assumed that these smaller vessels are used to remove smaller sections of cable. The energy demands of both large and small CLVs will be shown in appendix H.

### 9.1.5 Heavy Lift Vessels

For GBFs, jackets, and the substations, heavy lift vessels (HLV) are necessary. In the Seaweb database, little consumption data for these types of vessels were available. For this reason, it was assumed that these vessels would operate with engine loads relative to MCR similar to the data used for the other vessels.

Two types of heavy lift vessels were included in this assessment. Self propelled vessels, and heavy lift platforms (HLP). The self propelled HLVs were modelled on the *Seaway Strashnov* [64], and the heavy lift platforms, used for removal of substation top pieces, was modelled on the *Thialf* [65].

### 9.1.6 Vessel energy demand

In the tables above, only the energy demand when traveling is given. This is the data that was available from the Seaweb database [55]. For the energy demand when the vessels are operating or idling, some assumptions had to be made.

When the vessels are in DP mode, it was assumed that their energy demand was about half of what it is when the same vessel is traveling. This is based on a study conducted by Bø et al.[66], that found that vessels report using between 10-50% of engine power when in DP mode. When the vessel is in port, or otherwise idling, it was assumed that the energy demand was further halved, i.e. 1/4 of engine demand when traveling.

When vessels are operating in the vicinity of wind turbines, it was assumed they would be in DP mode. However, this assumption was not made for jack up vessels. For jack ups, the energy demand was assumed to be slightly less than 1/4 during operations.

This gives the following energy demand data for all vessels involved:

Table 7: Energy demand for every vessel, in different conditions.

| Condition | SPIV | AHTS | Large CLV | Small CLV | HLV | HLP | OSV |
|---|---|---|---|---|---|---|---|
| **Travel** | 8.2 | 7.4 | 9.3 | 5.2 | 18.9 | 0 | 6.3 |
| **WoW** | 4.1 | 3.7 | 4.7 | 2.6 | 5.7 | 6.6 | 3.2 |
| **Operations** | 3 | 3.7 | 4.7 | 2.6 | 5.7 | 6.6 | 3.2 |
| **Idle** | 2.1 | 2.3 | 2.4 | 1.3 | 2.9 | 3.3 | 1.6 |

For the full calculations of energy demand, see appendix H.

## 9.2 Wind Farm Data

In order to perform an assessment that is both useful, and that accurately portrays reality, data on several different wind farms was collected. The data was used to develop a basecase, that should reflect an ”average” or typical windfarm, as well as establish several other cases as a basis for comparisons.

### 9.2.1 Distance to shore/Travel Distance

Statistics developed by WindEurope [2] show that offshore wind farms are being moved increasingly farther offshore, see Figure 14. As the wind farms are moved farther away from shore, vessels performing the decommissioning will have to travel for longer, increasing fuel and energy usage. It will also impact what choice of vessels are available to perform the decommissioning, as they must be able to sustain long trips offshore, and carry the necessary fuel for the voyage. Smaller crew transfer vessel for example, will not be suitable for wind farms located more than 100km from its nearest port [67]. Figure 14 shows that in 2019, the average distance to shore for a wind farm was 60 km, and nearly doubling since 2017.

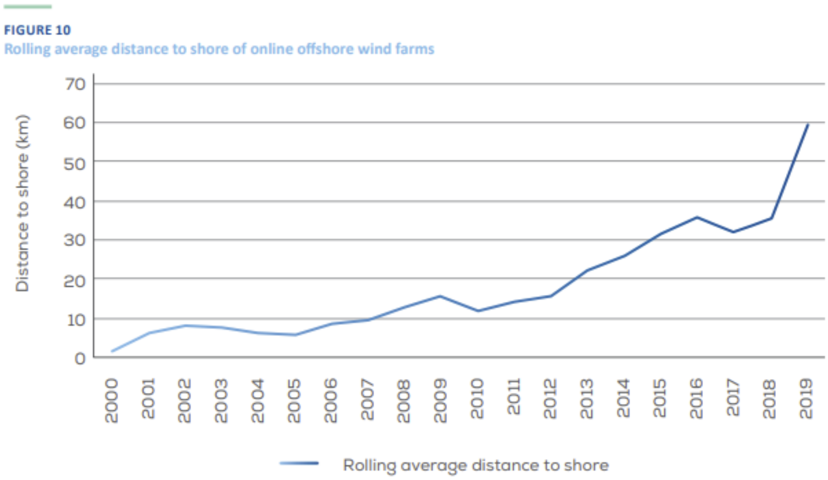


Figure 14: The average distance from shore to wind farms by year.

Source: From [2]

To establish the distance a decommissioning vessel would have to travel in order to reach a suitable port to conduct operations from, another 100 km was added to the distance between the wind farm and shore. As can be seen in Figure 15, following this assumption would cover about half of the west coast of England. The real-world distance to a suitable port depends on many factors, including availability, economics, and other project specific requirements. Since the purpose of the assessment is to evaluate how different wind farm parameters impact the GWP of decommissioning, the primary requirement for choosing travel distances between ports was to ensure results were consistent and comparable.

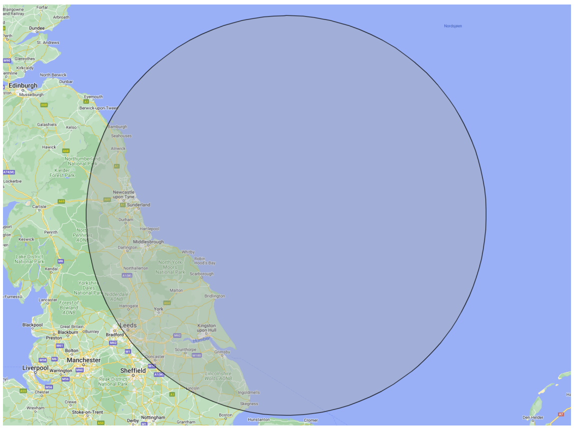


Figure 15: A radius of 200km with its centre 100 km away from the eastern coast of the united kingdom. The coastline inside the area of the circle has a length of more than 300 km.

Source: mapdevelopers.com

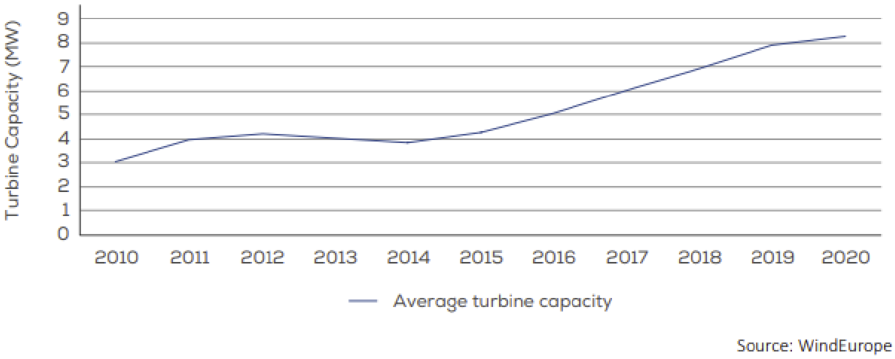
In the table below, a selection of planned and under construction offshore wind farms and their length to shore is shown. Most of them are located well over 100 km to shore, and some of them are located almost 200 km from shore. Based on these planned offshore developments, the distance to shore in the basecase will be set at 100km, which should somewhat reflect a normal shore distance. Additionally, and analysis effects of moving the wind farm further offshore, to 200 km, was also conducted, to find the effects moving substantially further offshore had on the results.

Table 8: Distances top the coast for a selection of offshore wind farms.

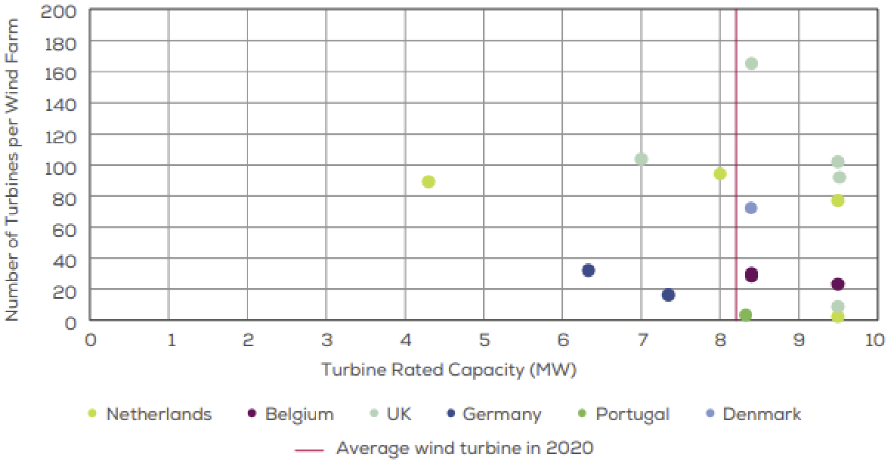
| **Offshore wind farm** | **Year operational** | **Length from shore [km]** |
|---|---|---|
| Doggerbank A [34] | 2026 | 131 |
| Doggerbank B [34] | 2026 | 131 |
| Doggerbank C [37] | 2026 | 196 |
| Hornsea 1 [68] | 2020 | 120 |
| Hornsea 2 [8] | 2022 | 89 |
| Sofia [69] | 2026 | 163 |

### 9.2.2 Turbine Size

Turbine size is generally expected to grow, both in rated power production, and in physical dimensions. This has implications for the vessel performing disassembly, which will be discussed in Section 9.1. For the wind farm, the only difference will be the power output per wind turbine.



(a) The average rated power of installed OWTs per year in Europe.



(b) The turbine ratings of all offshore wind farms installed in Europe in 2020.

Figure 16

Source: From [9]

Figure 16 shows that the capacity of installed offshore wind turbines has risen quite dramatically, doubling since 2015. For the assessment done in this assessment, the basecase will have average turbine sizes of 8MW. However, since turbine sizes are expected to increase, A wind farm case with 12 MW turbines was also included in the assessment.Turbines of this size are currently being installed in some offshore wind farms [34]. Additionally, a comparison with 4 MW turbines will also be conducted, as this is comparable to other LCAs [17, 19, 21].

### 9.2.3 Wind Farm Output/Size

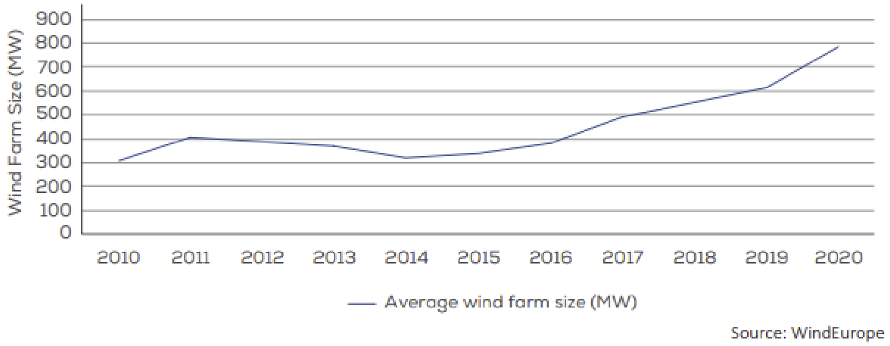


Figure 17: The average power production of offshore wind farms in Europe. From [9]

Figure 17 shows the average power production from offshore wind farms in Europe for the last decade. The average size is 788MW [9], so for the wind farm cases in this assessment, a total power capacity of 800 MW was chosen. The power output will be the same for all wind farms analysed in this assessment, which yields the following number of turbines:

Table 9: Number of turbines vs turbine rated power.

| **Turbine rating** | 4 MW | 8 MW | 12 MW |
|---|---|---|---|
| **No. of turbines** | 200 | 100 | 67 |

The last wind farm will have a power output of 804 MW, however, this will be accounted for in the results, by the functional unit.

### 9.2.4 Cables

As mentioned in Section 3, turbines in wind farms are connected with each other and the substation via the inter array cables, and connected to the rest of the power grid through the export cables.

The length of cables that need to be removed for a decommissioning is assumed to be much smaller than the length of cables that are installed. While regulations generally require the seabed to be restored to its original condition,as mentioned in Section 5, the removal of cables are often considered by many decommissioning to be an unnecessary toll on the seabed [34, 37, 36, 8]. The decommissioning plans describe letting the cables be buried in situ, unless some sections of the cables are exposed [8, 34, 37, 33]. For this assessment, it was assumed that 10% of the export cables are exposed, and will need to be removed by a small CLV. As for the inter array cables, it was assumed that they will not need removal, or that the ROV decommissioning preparation vessel will bury any exposed cables.

Additionally, a scenario where all export cables are removed was also included in the assessment, as some wind farm operators plan to remove all of the export cables [70].

The amount of export cable for the wind farm will be assumed to be tied to the given distance to shore. In the table below, The relation between the wind farm's distance from shore and the total length of export cable is shown. The average is around 4, which will be used to determine the length of export cables in this assessment. This gave a cable length of 400 km for windfarms 100 km from shore.

Table 10: The ratio between cable length and distance to shore

| **Wind Farm** | **Length of cable [km]** | **No. of cables** | **Ratio** |
|---|---|---|---|
| Sheringham Shoal | 21.6 | 2 | 2.2 |
| Doggerbank A&B | 190 | 4 | 5.8 |
| Doggerbank C | 263 | 2 | 2.7 |
| Gwynt y môr | 82.5* | 4 | 5.5 |
| Hornsea 2 | 423 | N/A | 4.8 |
| Dudgeon | 42 | 2 | 2.6 |
| Average | - | - | **3.9** |

It was assumed that, on average, the vessels will operate at a speed of 2 kt when they are removing cable sections. They will then move at a reduced machinery load, similar to that of a DP-condition. Suitable vessels for cable retrieval can be any vessel with ROV capabilities, and capacity for storing the removed cable on board. This can include OSVs, some AHTSs, CLVs, and specialized cable repair vessels. However, if more than 10% of the export cables (40-80km) need to be removed, a larger specialized CLV may be the only vessel suitable. A vessel such as *Nexans Aurora* is able to carry 10 000 Te of cable [71], or roughly equal to 200 km [16].

In the table below, the expected durations of the cable removal operation for each scenario are presented.

Table 11: Duration of cable removing operations, by length of cable to be removed

| **Length removed** | 40 km | 80 km | 400 km |
|---|---|---|---|
| **Time spent on removal [hours]** | 10.8 | 21.6 | 108 |
| **Type of vessel needed** | Small CLV | Small | Large CLV |

### 9.2.5 Foundations

Monopiles are the prevalent type of foundations today. A rundown by WindEurope finds that out of 14 offshore wind farms being installed in Europe in 2020, only 4 use another type of foundations: Two with jacket foundations, and two floating wind farm projects. For the basecase, monopiles will be used for the foundations.

### Monopile Foundations:

A review of some decommissioning plans for planned and current wind farms show that all none of them include a plan for the complete removal of foundations. Instead, they expect cutting the piles below the seabed is the most practical solution [54, 34, 37, 33, 8, 36].

Table 12: Plans for removal of monopiles in decommissioning plans.

| **Wind Farm** | **No. of Foundations** | **Foundation Type** | **Foundation removal** | **Estimated time** |
|---|---|---|---|---|
| Sherringham Shoal | 88 | Monopile | Cut below seabed | N/A |
| Doggerbank A & B | 190 | Monopile | Cut below seabed | 2.8 days |
| Doggerbank C | 87 | Monopile | Cut below seabed | N/A |
| Gwynty Môr | 160 | Monopile or GBF | Cut below seabed (mono), Complete removal (GBF) | N/A |
| Hornsea Project 2 | 165 | Monopile | Cut below seabed | N/A |
| Dudgeon | 67 | Monopile | Cut below seabed | N/A |

From the decommissioning plans it is clear that a complete removal of monopile foundations is unlikely to be the preferred option. It will therefore not be considered in this thesis. In the case of the GBFs, complete removal may be the only possibility, because the typical depth of offshore wind installations make leaving any part of them on the seafloor an unfeasible solution, as discussed in Section 5.

Some foundations may require scour protection. For this analysis, the assumption is that it will not need removal and transportation away from the wind farm. This is in line with the decommissioning plans from Table 12. Some studies also suggest that leaving scour protection behind may be beneficial for marine habitats as well [23].

Table 13: Installation times for monopile foundations. From [16]

| **Wind Farm** | **No. of Foundations** | **Foundation Type** | **Foundation Time** |
|---|---|---|---|
| Horns Rev 1 | 80 | Monopile | 3 days |
| Horns Rev 2 | 91 | Monopile | 1.8 days |
| North Hoyle | 30 | Monopile | 5.5 days |
| Scroby Sands | 30 | Monopile | 3.5 days |
| Kentish Flats | 30 | Monopile | 2 days |
| Lynn & inner Dowsing | 54 | Monopile | 4.4 days |
| Barrow | 30 | Monopile | 7 days |
| ”OWEZ” | 36 | Monopile | 3.3 days |
| Burbo Bank | 25 | Monopile | 2.2 days |
| Princess Amalia | 60 | Monopile | 3 days |

The table above shows that monopile foundations take an average of around 3 days to install. A review of some decommissioning plans also reveal that expected removal times for foundations in even larger wind farms are similar to the installation times presented in the report: around 3 days per foundation for monopiles [34]. It was therefore assumed that to remove a monopile foundation would take 3 days on average.

### GBF and Jacket Foundations:

However, not all foundations are of the monopile variety. Jackets and GBFs are also used for some turbines, as well as for the offshore substation. In the decomissioning plans, the anchoring piles for the jackets are often cut in a similar fashion to the monopiles, before lifting them using a HLV. The GBFs will have to be removed in its entirety. This presents a challange as vessels capable of lifting and transporting foundations weighing sometimes more than 2500t will be needed [10].

Table 14: Installation times for GBFs. From [16]

| **Wind Farm** | **No. of Foundations** | **Foundation Type** | **Foundation Time** |
|---|---|---|---|
| Middelgrunden | 20 | GBF | 3 days |
| Nysted | 72 | GBF | 5.3 days |
| Lillgrund | 48 | GBF | 8.8 days |

According to the statistics from BOEMRE's report, GBFs take significantly longer than monopiles to install. This is expected, as GBF removal is a process that requires specialized vessels that both travel and operate more slowly than SPIVS. Also, installation of GBFs require more vessels to be used concurrently. Due to the lack of expected removal times of GBFs and jackets in decommissioning plans, the removal time of jackets and GBFs was assumed to be similar to the average time for GBFs from the BOEMRE report: 5.7 days.

On the basis of the installation times in the table above, and the expected removal time from the Dudgeon decommissioning programme, the average time for the removal of each type of foundation is as follows:

Table 15: The removal time for each foundation type.

| **Action** | **Monopile** | **GBF** | **Jacket** |
|---|---|---|---|
| WoW | 12 h | 12 h | 12 h |
| Operations | 60 h | 116.4 h | 116.4 h |
| In port | 24 h | 24 h | 24 h |
| Average time per foundation* | 3 days | 5.7 days | 5.6 days |

*Includes travel time for backloading, which is why jackets and GBFs have slightly different times.

The capacity of the barges needed to remove the foundations is assumed to be 5 for monopile foundations, 2 for GBFs, and 3 for jackets. This is based on the total weight of all foundations, about 5000 tonnes. Since jackets are transported faster than GBFs, the average time to decommission jackets is slightly lower than for GBFs.

For all foundations, a period of WoW of 12 hours is assumed, and each time is in port, it was assumed it would remain in port for 24 hours before returning to the wind farm. These times are shown in Table 15.

### 9.2.6 Using Specialized Vessels for GBF and Jacket removal

As well as the traditional methods for removal as described in BOEMRE's report, and Gwynt y Môr's decommissioning programme [16, 33], an assessment was done using a new vessel on order for Seaways 7, the *Seaway Alfa Lift* [72]. Once completed, this vessel will be able to both carry and install offshore wind foundations, potentially removing the need for using both heavy lift vessels, and barges and tugs.

The *Seaway Alfa Lift* has a loading capacity of 8 1500 Te jackets, or roughly 5 GBFs. It has a crane capable of lifting 3000 Te, more than the weight of wind turbine foundations. This vessel will be used as a basis for carrying capacities for a comparison between using traditional methods for jacket and GBF removal, and using special purpose vessels. The energy sue of such a vessel was considered the same as a typical self propelled HLV vessel, sea Table 7.

Figure 18: An illustration of the Seaway Alfa Lift carrying jackets.

Source: Ulstein [73]

### 9.2.7 Substations

It was assumed that there are always two substations per wind farm, regardless of any other factors. They will be installed on jacket foundations, and will require HLPs to disassemble. This is based on descriptions from decommissioning plans [8, 54, 34, 37]. Both the jacket and top piece will be transported back to shore on a barge towed by an AHTS, one at a time.

The time it takes to remove the foundations will be the same as for a typical jacket foundation, see Table 15. However, for the top piece, there is little data and statistics available. The BOEMRE report [16], found that installation of the top piece of the substation has taken anywhere from a few months to four days. For this assessment, the removal of the top piece was estimated to be completed in 100 hours, or a little over four days.

### 9.2.8 Lifetime

The lifetime of the wind farm and all its components was assumed to be 25 years. This is the expected lifetime cited in several decommissioning plans. It is also close to the lifetime of the offshore wind farms that have been decommissioned previously [23]. In the table below, the lifetime of a selection of offshore wind farms is shown.

Table 16: The lifetime of offshore wind farms.

| **Wind farm** | **Life time [years]** |
|---|---|
| hline Yttre Stengrund | 15 |
| Lely | 20 |
| Vindeby | 26 |
| Utgrunden 1 | 18 |
| Blyth | 13 |
| Beatrice Demo | 8 |
| Sheringham Shoal | 20* |
| Doggerbank A/B/C | 25* |
| Gwynt y môr | 20-23* |
| Hornsea Project 2 | 25* |
| Dudgeon | 25* |

*Expected lifetime, has yet to be decommissioned.

The first five wind farms in the list are wind farms that have reached their end of life, and been decommissioned after the stated amount of years. The data in general show that 25 years is a good assumption for the life time of an offshore wind farm.

The lifetime was used to establish the total power production for the offshore wind farms that were considered in this thesis.

### 9.2.9 Dismantling of Turbines

Decommissioning plans and literature treat the dismantling of turbines as the reverse of the installation procedure. Because of this, data and statistics on installation was used to estimate the duration of turbine disassembly. As a large number of offshore wind farms have been installed in the last decade or two, so statistics are available on typical installation times for offshore wind turbines.

The data in the following table is a summary of statistics found in the report from BOEMRE [16].

Table 17: Installation Times per Component for Various Offshore Wind Farms

| **Wind Farm** | **No. of turbines** | **Turbine size [MW]** | **Turbine time** |
|---|---|---|---|
| Middelgrunden | 20 | 2 | 3.8 days |
| Nysted | 72 | 2.3 | 1.3 days |
| Lillgrund | 48 | 2.3 | 1.6 days |
| Horns Rev 1 | 80 | 2 | 3 days |
| Horns Rev 2 | 91 | 2.3 | 2 days |
| North Hoyle | 30 | 2 | 6 days |
| Scroby Sands | 30 | 2 | 3.8 days |
| Kentish Flats | 30 | 3 | 4 days |
| Lynn & inner Dowsing | 54 | 3.6 | 1.9 days |
| Barrow | 30 | 3 | 5 days |
| ”OWEZ” | 36 | 3 | 2.9 days |
| Burbo Bank | 25 | 3.6 | 1.8 days |
| Princess Amalia | 60 | 2 | 9.5 days |

In addition to the statistics presented in Table 17 above, some decommissioning programmes also specify the expected or likely times for the complete decommissioning of the wind farm. They mostly show similar times as the table above, estimating typically 2 days per turbine.

Table 18: Descriptions of turbines in decommissioning plans

| **Wind Farm** | **No. of turbines** | **Turbine size [MW]** | **Expected disassembly time** |
|---|---|---|---|
| Sheringham Shoal | 88 | 3.6 | 2.3 days |
| Doggerbank A & B | 190 | 12 | 2 days |
| Doggerbank C | 87 | 14 MW | N/A |
| Gwynty Môr | 160 | 3 & 5 | N/A |
| Hornsea Project 2 | 165 | 8 | N/A |
| Dudgeon | 67 | 6 | N/A |

Based on these sources, it was assumed that the dismantling operation of a wind turbine would take 30 hours. Additionally, it was assumed that, on average, the vessels will spend 12 hours WoW for each wind turbine. When the vessels are in port, it was assumed they would idle for 24 hours. In the end, this resulted in an average time of 2.1 days per turbine, once travel time is included as well. For different size turbines, the travel times are slightly different, affecting the average time per turbine. The exact average times per turbine can be found in the appendix.

## 9.3 Floating Wind Farm

An assessment was also done on the removal of a floating wind farm. The data was based on the decommissioning programme of Equinor’s Hywind Tampen project [30].

An AHTS will disconnect mooring lines between the anchors and the spar buoy, as well as the dynamic parts of the electrical cable from the turbine. It was assumed the vessel will spend 10 hours doing this. The vessel will return to port once it has reached its capacity for carrying cables or anchor chains. The capacity is based on Normand Sapphire's anchor locker [74, 75]. The calculations for the storage capacity can be seen in appendix J.

The vessel will then tow all wind turbines and their foundations back to port, at a speed of 6 kt. The removal of cables and substations is the same as for the basecase.

### 9.4 The Scenarios

The table below presents all the different wind farm cases that were considered in this assessment.

Table 19: noe

| | **Basecase** | **Bascase+100km** | **GBF** | **Jacket Foundation** | **200x4MW** | **67x12MW** | **Floating** |
|---|---|---|---|---|---|---|---|
| **No. of turbines** | 100 | 100 | 100 | 100 | 200 | 67 | 100 |
| **Turbine rating [MW]** | 8 | 8 | 8 | 8 | 4 | 12 | 8 |
| **Farm output [MW]** | 800 | 800 | 800 | 800 | 800 | 804 | 800 |
| **Lifetime output [GWh]** | 175200 | 175200 | 175200 | 175200 | 175200 | 176076 | 175200 |
| **Foundations** | Monopile | Monopile | GBF | Jacket | Monopile | Monopile | Spar |
| **Distance to shore [km]** | 100 | 200 | 100 | 100 | 100 | 100 | 100 |
| **Distance to port [km]** | 200 | 300 | 200 | 200 | 200 | 200 | 200 |
| **Export cable length [km]** | 400 | 800 | 400 | 400 | 400 | 400 | 400 |

# 10 Results

## 10.1 The Effect of Different Turbine Ratings

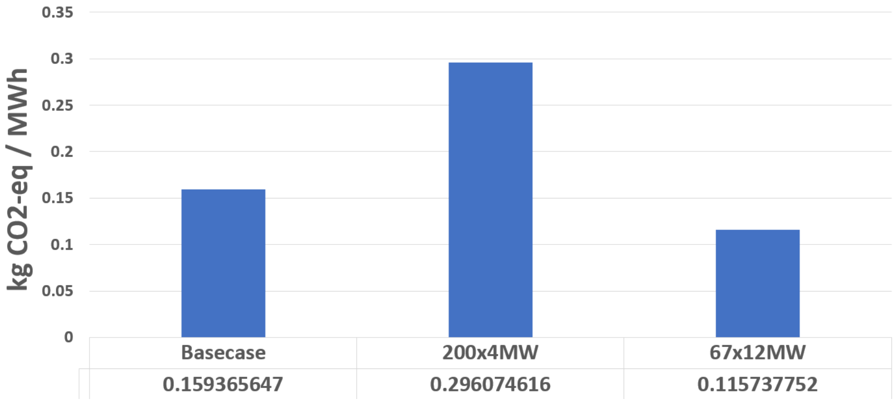


Figure 19: The GWP of wind farms with different turbine power ratings, normalized by MWh

Figure 19 shows the GWP of wind farms with different turbine power ratings. The results have been normalized to show kg $CO_2$ equivalents per MWh produced over the life time of the wind farm, as discussed in Section 8.

The results from the base case scenario should represent GWP of the decommissioning for a just installed or soon-to-be installed offshore wind farm. The most significant GWP contributions come from the jack up SPIVs and AHTSs, making up 50% and 43% of total GWP contributions. The other involved vessels, contribute about 7% all together. In Figure 20, the contribution of each vessel type is shown. This result is similar for the other wind farm cases.

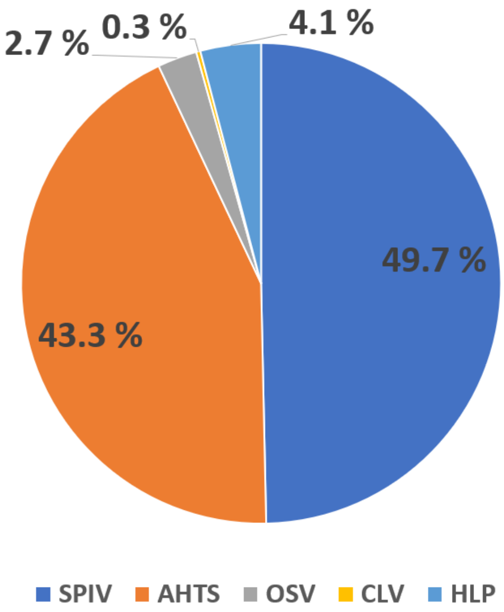


Figure 20: The share of GWP contributions per vessel type

### 10.1.1 The Effect of Changing the Number of Turbines

Changing the rating of the turbines implicitly changes the number of installations, in order to maintain the same total power production for the wind farm. Some parts of the decommissioning operation are unaffected by the number of turbines, such as the activities related to the dismantling of the substation and the export cables. However, the number of turbines is directly tied to the use of jack ups for disassembly, and barges and AHTS for transport of foundations and WTGs.

The share of the entire decommissioning process taken up by the ”constant” processes of disassembling substations and export cables increases as the number of turbines decreases and vice versa. This leads to a disproportionate change in GWP compared to the number of WTGs in each farm. The table below shows the GWP per turbine and foundation disassembly.

Table 20: The GWP per turbine disassembly for different wind farm sizes

| **Wind Farm** | 67x12MW | 100x8MW | 200x4MW |
|---|---|---|---|
| **GWP [Te $CO_2$-eq]** | 304.16 | 279.21 | 259.36 |

Table 20 shows that keeping all other factors the same, the GWP is lower for larger farms.

### 10.1.2 Returning foundations with SPIV

Another option, as mentioned in Section 9, is to backload the monopiles with the installation vessel, instead of using a barge. The result is a decrease in use of AHTS vessels, at the cost of more jack up SPIV use. In practice, this means AHTSs will not be used until the removal of the substations, which represents a large portion of the decommissioning process.

Table 21: The GWP when transporting foundations back on the SPIV

| Impact Category | Value |
|---|---|
| **GWP** | 0.11 kg $CO_2$-eq |

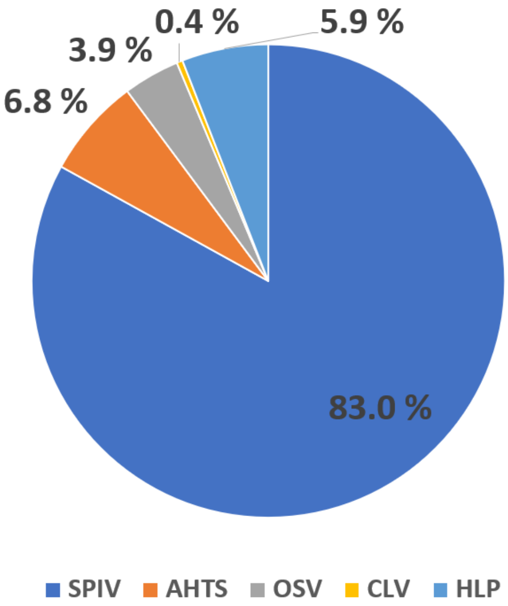


Figure 21: The share of GWP contributions per vessel type

Figure 21 shows that most of AHTS' contributions are taken up by the SPIVs. Table 21 also shows a significant reduction in GWP all together, as two vessels no longer need to operate concurrently.

However, this method also leads to a significant increase in use of the SPIV, almost by 10%. This can have some cost implications as day rates for AHTS' and SPIVs are very different. A basic cost assessment has been performed in this thesis, see Section 11.8.

Decommissioning plans however, suggest that such an approach may not be feasible for jack up SPIVs currently in use. An offshore wind installation vessel typically carry turbine towers vertically, bolted to the deck, see Figure 22. Such a configuration is not possible with monopiles, and the length of the piles may be longer than the width of the vessel. The vessel in the picture is around 40 metres wide, and the expected length of the removed monopile from the Hornsea 2 project is around 50 metres [8]. This makes it an unlikely method to be used for a majority of wind farms.

Figure 22: A typical jack up SPIV with turbines mounted vertically to the deck.

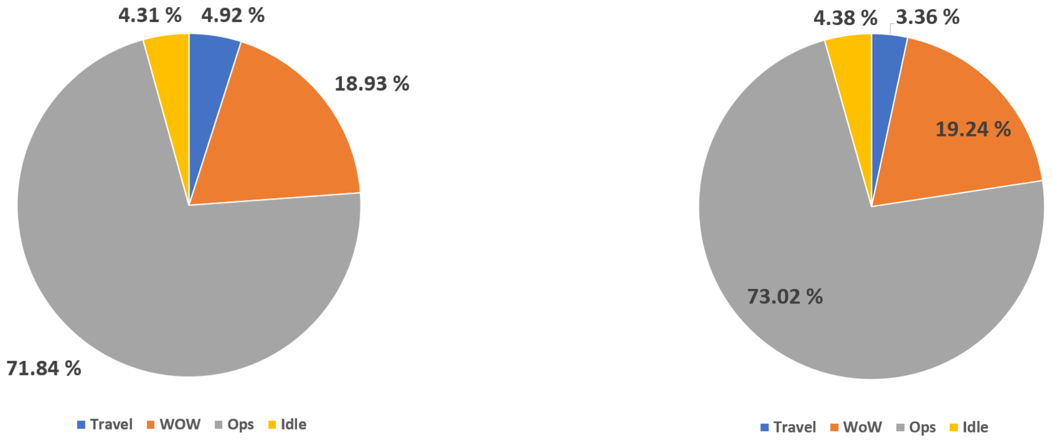
Source: Renewables Now [76]

## 10.2 Effects of Moving Farther Offshore

Table 22: The results of the wind farm 200 km from shore

| Impact Category | Value |
|---|---|
| **GWP** | 0.17 kg $CO_2$-eq |

Doubling the distance to shore leads to an increase of GWP of approximately 8%. Figure 23 shows that only 5% of the installation vessel's time at sea is spent traveling back and forth between the port and the wind farm. For the basecase the number is around 3%. However, as the vessel is under greater engine load during travel, the increase in GWP is slightly higher than just the increase in vessel use for AHTS and SPIVs. This implies that in order to reduce GWP, reducing the amount of travel required will have a bigger impact on the reduction of GHG emissions than effectivization of marine operations. Reduction of travel can be accomplished by carefully optimizing the base of operations, or by increasing the carrying capacities of vessels.



(a) The share of time when the jack up vessels are in different conditions, for the wind farm 200 km from shore.

(b) The share of time when the jack up vessels are in different conditions, for the base case wind farm

Figure 23: Notice how for the wind farm further out, time spent traveling has only increased 2%, yet the GWP rose 8%.

Farther out at sea, the wind strength also increases allowing for greater average power generation output. However, a review by Berlinski & Connors[11] estimates this effect to account for an extra m/s of wind if the wind farm is moved an additional 400 nm out. For this assessment, such considerations were not made, as all results were compared to the theoretical maximum power generation from each wind farm.

Additionally, moving further out requires longer export cables. Since the assumption made in Section 9.2.4 was that 10% of the cable would be removed, regardless of length, moving the wind farm further offshore will also lead to more cable needing to be removed by a cable vessel. However, because of the small contribution made by the cable vessels in the first place, this effect is marginal. If more or all export wire needs to be removed, the situation may be different, this will be further discussed in Section 10.4.

## 10.3 Different Foundations

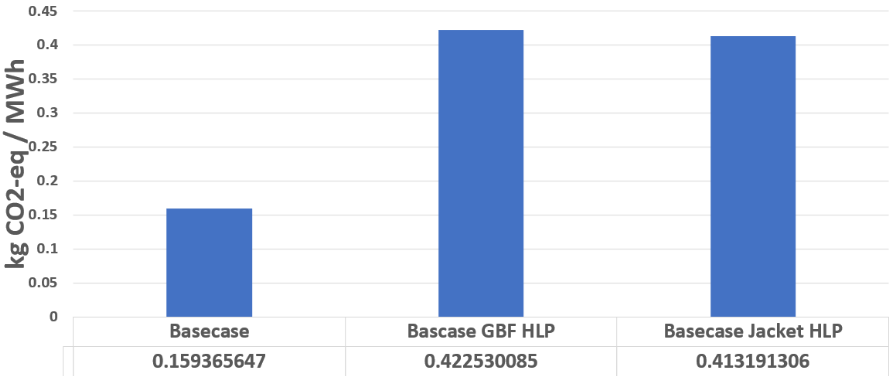


Figure 24: The GWP of different foundation solutions

The results show that because of the extra required vessels, such as the lifting vessels and extra barges and tugs, the GWP for jacket and gravity based foundations are much higher than for the base case, in fact more than double. Figure 26 shows that vessel use is much higher for the jacket and GBF foundations. This is expected, as the foundations are heavier, therefore more trips by the AHTSs and barges are needed. Additionally, the HLP will require AHTSs on its own for towing to the site, and between the wind turbines.

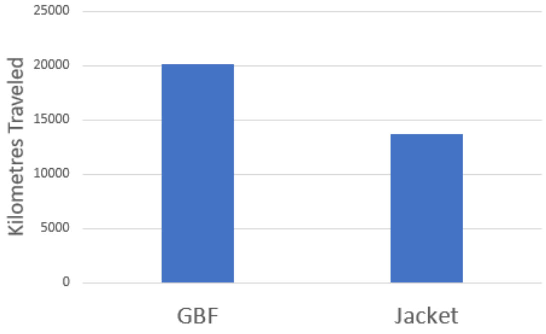


Figure 25: The distance AHTS and barge travel for jacket and GBF foundations.

The results are somewhat different for jackets and GBFs, mostly due to the different weights and sizes of the foundations, allowing the barges to carry more jackets for every trip. In the graph above, the differences in travel distance for the AHTSs is shown. The barges carrying GBFs have to return to port 50 times to decommission the wind farm, while the barges carrying jackets only have to return 34 times.

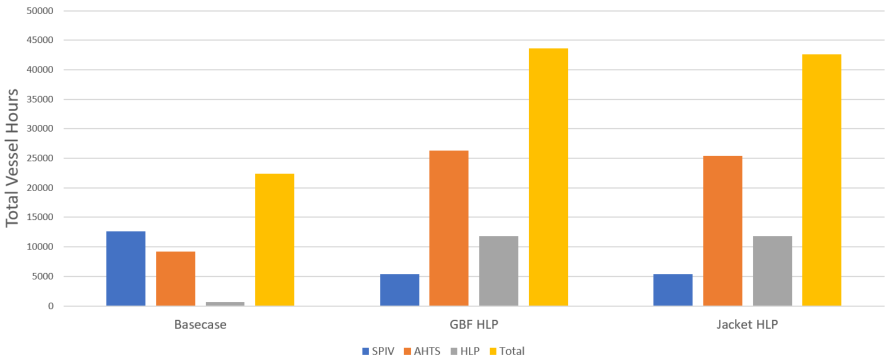


Figure 26: The total vessel hours for each type of vessel, compared when decommissioning different types of foundations.

Moreover, the removal of GBFs and jacket foundations take longer time. As discussed in Section 9.2.5, the installation times suggest that decommissioning of GBFs and jackets will two extra days compared with monopiles. This also contributes to the rise in vessel use.

### 10.3.1 Use of Specialized OWT Foundation Vessels

As discussed in Section 9.2.6, new specialized vessels are being planned and ordered for offshore wind use. Taking such newer vessels into consideration, such as the *Seaway Alfa Lift*, the results are changed significantly. Since the vessel is able to both execute the required lifts and backloading of the foundations, fewer AHTSs and and bareges are needed to perform the disassembly. This leads to a reduction in GWP, as seen in Figure 27.

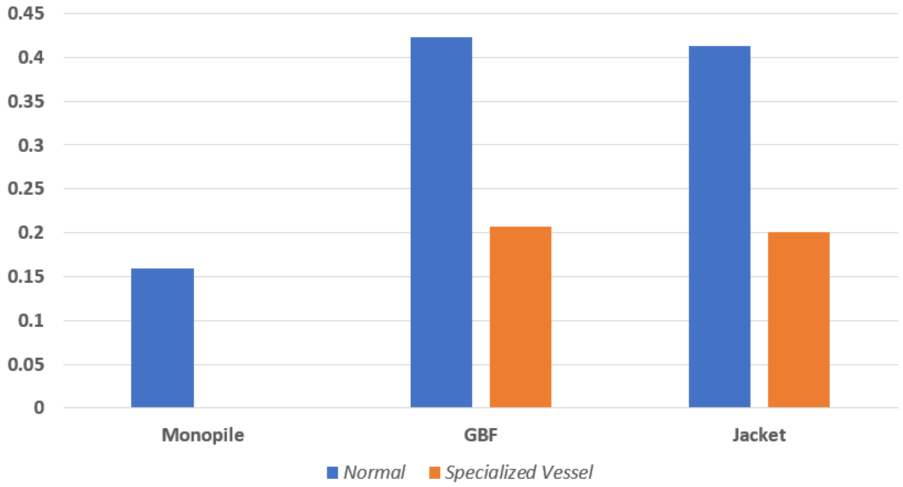


Figure 27: The GWP of different foundation lifting solutions. The GWP when using the specialized HLV is shown in orange bars.

Using such vessels will allow for the installation and removal of offshore wind installation to have a GWP be almost as low as for monopile installations, regardless of their foundation type. This can lead to a reduction in the GWP of wind farms situated in deeper waters, were GBFs and jackets may be required.

However, it should be pointed out that such vessels are not in operation yet. Some float-on/float-off jacket transportation vessels exist, which allows the vessels to unload the jackets at sea, but not precisely manipulate their position as they are not equipped with a crane. These vessels will therefore be unsuitable for removal of jacket foundations

## 10.4 Cables

Removing all export cables would result in a 4 times increase in the share of GWP contributed by the cable vessel. The total increase represents another 3g of $CO_2$-eq per MWh production from the wind farm. This is both due to the extended period the cable vessel is required to operate, but also because of the assumption made in Section 9.2.4, that a larger CLV will be needed, similar to the *Nexans Aurora*. These vessels have larger installed machineries, and will therefore have a larger GWP impact.

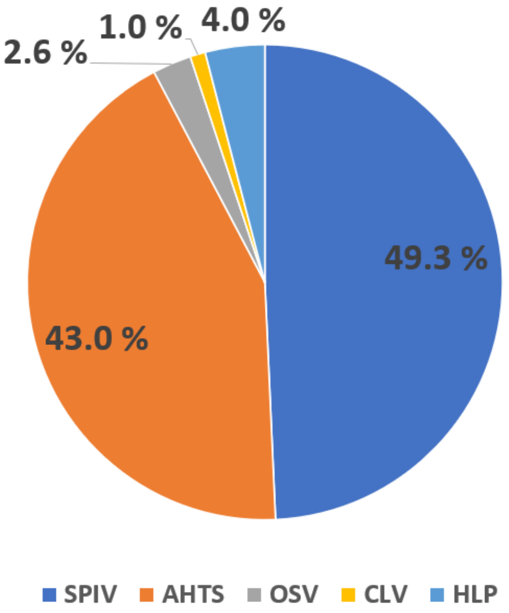


Figure 28: GWP contribution by vessel type. Note how the contribution from the CLVs have increased, compared with Figure 20.

Some studies find that unnecessarily removing the buried parts of the cables will cause more damage to the seafloor, than leaving the cable buried in situ [27, 23, 77]. Together with the increased GWP from superfluous vessel use, removing all the cables is not a a recommended course of action.

However, some users of the sea, primarily fishers are worried about offshore wind in general reducing the areas available for fishing. Fishers in the UK lodged complaints against Hornsea project 2's decommissioning programme [8], because the cables were planned to be left buried in situ. Their primary worry was that fishing equipment would be damaged by exposed cables. A complete removal of cables may be the only way to ensure that no cables are ever exposed.

### 10.5 Floating Offshore Wind Farms

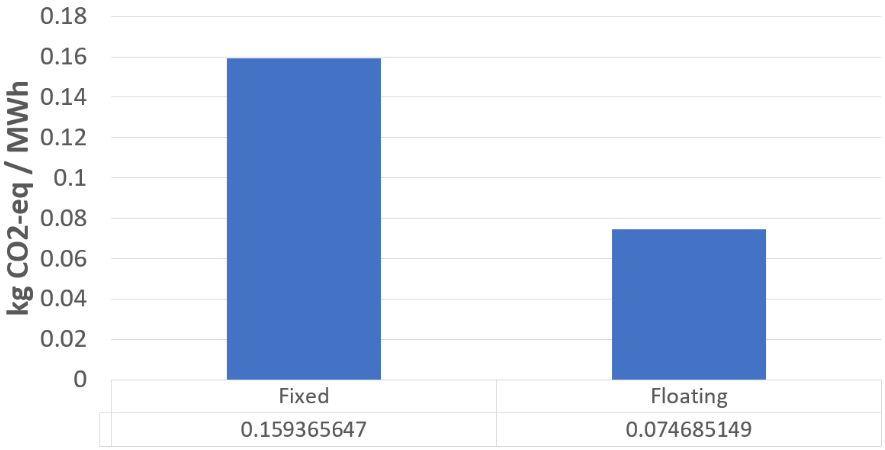


Figure 29: The GWP of the fixed basecase wind farm and a floating windfarm. GWP in kg $CO_2$-eq/MWh.

The results from the decommissioning operations of the floating wind turbine shows that emissions related only to the marine operations for floating turbines are significantly lower than for fixed turbines. This is expected, as the vessels remain at sea for far less time, as no disassembly of the turbine is taking place offshore. The results show that an impact assessment of floating wind needs to include the complete end-of-life (EoL) cycle, including final disassembly at a yard, and recycling of the materials, in order to be comparable to an assessment of fixed offshore wind.

## 11 Discussion

### 11.1 Evaluation of the Data and Assumptions

One of the largest challenges with the data collection was the lack of any meaningful statistics and previous experiences with offshore wind decommissioning. As mentioned previously, only very few offshore wind farms have previously been decommissioned, and the ones that have been decommissioned have been small scale developments that are no longer representative of current offshore wind farms.

The use of installation data as a substitute for decommissioning data has been previously done by others [18, 19, 21], and is often cited as the expected procedure when end-of-life is reached [15, 5]. However, while certain parallels can be drawn between some stages of decommissioning and installation (eg. hammering the monopile - cutting the monopile), more data is needed to accurately model the differences between the two stages of the lifecycle.

The installation duration times provided by BOEMREs report is quite old ( 2011), and may also no longer reflect the current level of technology. However, the data in the report fits well with the expected time for removal of WTGs and foundations that are presented in some of the decommissioning plans. These plans have however been criticized for their inaccuracies and are often somewhat lacking when describing precisely the decommissioning operations entail [24]. However, for the purposes of the assessment conducted in this thesis, the data from these decommissioning was often the best available.

The energy use of the vessels considered in this assessment was based on consumption data when traveling at service speed from the Seaweb database [55]. There is no guarantee for the accuracy of the consumption data provided, however, a cross check with the vessels' installed machinery MCR shows that their energy demand falls within 50-60% of their total installed MCR (including auxiliary generators). This is the expected value, as marine machinery typically operates on 70% of installed capacity when under way [78]. Additionally, the conversion from fuel usage in tonnes to energy was based on a typical marine diesel engine specific consumption, as provided by the engine supplier. This consumption figure may be overly optimistic, and may only reflect the consumption when running the engine during absolute optimal conditions.

In general, the results are considered to be robust. The global warming potential is of similar size to other previous work, with some expected differences as methodology and level of detail are different. The differences in results between different cases were as expected, and of a similar magnitude.

## 11.2 Assessment of the Methodology

As stated in the ISO standard [42, 41], the methodological choices should be compatible with the goals of the study. The choice of system boundaries, functional unit, and the data used in the assessment could all have big impacts on the results. The goal of this study was to make a comparison between different offshore wind farm, and the differences between varying methods of decommissioning.

The functional unit was chosen as the one MWh of rated energy production, over the life time of the wind farm. This is a choice that may not accurately reflect reality, however, it makes comparisons between different sites easier. Wind conditions are different at every site, and actual electricity production could vary significantly.Take for instance the basecase of this thesis, and the comparison with the windfarm 200 km from shore. In reality, one would expect the latter to produce more electricity, as wind speeds generally increase further from shore [11]. The chosen functional unit was still able to provide results that could be compared.

In this assessment, only the emissions from the marine operations were considered. Emissions related to the final dismantling, recycling and over land transportation of the decommissioned wind turbines and foundations were not considered. This may be important in the consideration of different turbine sizes, as the methods and amount of material to be recycled may not be the same for different turbines and foundations.

## 11.3 On Floating Offshore Wind

For an assessment of the GWP of floating offshore wind, a larger part of the EoL stage will have to be included in order to obtain results that are comparable with the decommissioning of fixed offshore wind. The process is too different to make a viable comparison, within the scope of this thesis.

## 11.4 The Most Influential Wind Farm Parameters

The use of jacket or gravity based foundations had a much larger effect of the GWP than other parameters of the windfarm. This result was expected, as it was assumed that these foundations would take longer to install than the more commonly used monopile foundations. However, as mentioned in Section 11.2 and in Section 10.2, the effect of different wind speeds were not taken into account. Moving wind farms farther offshore into deeper waters will require the use of different foundations [10], but will also increase wind speeds [11]. The increased power production may in some cases offset the larger environmental footprint produced by GBF and jacket foundation types.

The foundations had a greater impact on GWP than changing the number and rating of the wind turbines. A doubling was seen in the emissions when decommissioning monopile foundations compared with GBFs, but the same was not seen when the number of wind turbines was doubled. This "economies of scale" effect implies that although the removal of cables and substations take up a relatively small portion of the entire decommissioning process, the number and types of vessels required for the operation make the impact of these parts disproportionally large. This is especially true for the dismantling of substations, as it requires energy demanding HLPs in addition to a large number of support vessels, such as AHTSs.

Moving the offshore wind farm farther away from the shore had a surprisingly low impact on the overall GWP. During travels, ship machinery is under more load than during operations, so a larger effect than the 7% increase in GWP was expected when doubling the travel distance of all vessels involved.

## 11.5 Effects not Considered by This Assessment

In this thesis. only the global warming potential, or release of greenhouse gases in kg $CO_2$-equivalent, was considered. However, the decommissioning operations can affect the environment in other ways than through green house gas emissions.

### 11.5.1 Sound

Some parts of the decommissioning process can be noisy, and this noise may have an effect on marine animals in the vicinity of the wind farms. This is particularly true when operations involve cutting piles, such as for monopile and jacket foundations.

A study conducted by Hinzmann et al.[79] found that sound levels were as loud as 150 dB 50 metres away. These values were still low enough to be within established sound emission limits for pile hammering. However, the sound from the cutting tool was different from the single sound events from a pile hammer, in that the sound from the cutting tool was continuous over the operation, which lasted approximately 30 hours.

This makes the sound pollution from the pile cutting different from the sound emitted by seismic exploration, whose impact on marine life has been extensively studied. A large study by Meekan et al.[80] however, found that fish showed no long term reactions to the emissions from seismic exploration. Although the sound emitted from seismic exploration is different from the sound caused by the cutting of piles, the sound from seismic charges are much louder than those of cutting (up to 250 dB in the study), and can go on for a time frame similar to that of a wind farm decommissioning.

### 11.5.2 Effect on the Seabed and Habitats

In this assessment, only partial removal of substructures were considered. These structures can be of disturbance for marine life near the wind farm, but removing them may also cause damage to the sea bed.

The effects of the disruption of marine life and habitats caused by the decommissioning activities, such as dredging, trenching of cables, and moving of scour protection was not covered in this assessment. Part of the reason is that these habitats would have been equally disturbed during the installation of the wind farm, and because the effects on marine life has already been assessed in publicly available environmental impact assessments (EIA) published in conjunction with decommissioning programmes.

A study of these programmes conducted by Hall et al. [77] shows that in general, the stated environmental impacts of offshore windfarms are not significantly different their onshore counterpart, however there are potentially more impact categories for offshore wind farm developments. However, their paper also criticized how the EIAs often assumed that decommissioning was simply an "undoing" of the installation. Hall et al., however, argued that removing something from the marine environment, is different from adding something to it.

This view is shared by Smyth et al.[27]. In their paper, they argue that leaving some structures behind above the sea floor may be beneficial for marine life, as they may act as artificial reefs. This has been attempted with some success in the gulf of Mexico with oil and gas installations. However, offshore wind farms are generally situated in much shallower water than what is found in the gulf of Mexico [2], and leaving structures behind may disturb navigation and use of the area, particularly for fishers. The Norwegian petroleum directorate requires that at least 55 metres remain between the top of the structure and the sea surface [35]. This makes it unfeasible to leave any part of offshore wind structures above the ocean floor.

## 11.6 Technology maturation

The level of technology assumed in this assessment has been the current or very near-future. This may not be the best choice, because, as mentioned in the introduction, most offshore wind installation are due for decommissioning in another 20-30 years. However, making assumptions of what solutions or methods are most common at that time is unrealiable, and makes data collection even more difficult. However, it is expected that decommissioning techniques will mature, both in efficiency and lead to reductions in environmental impacts [28].

## 11.7 Comparisons to Previous Work

Several LCAs considering the entire lifecycle of offshore wind power have been conducted. Most of these have not had a strong focus on decommissioning operations, or marine operations in general.

### 11.7.1 Weinzettel et al., 2008 [19]

Weinzettel et al. conducted a life cycle assessment of a floating offshore wind farm. Their wind farm consisted of 40 5MW wind turbines, which is smaller than the wind farm sizes considered in this thesis. They assumed a lifetime of 20 years, similar to the lifetime used in this thesis.

For the end of life scenario, they assume the GWP of decommissioning activities is exactly the same as the GWP from the assembly of the wind farm, however it is not clear exactly what this encompasses. The results from the assessment shows emissions of $3.2 * 10^{-3}$ kg $co_2$-eq / MJ, or 11.52 kg $CO_2$-eq / MWh. However, they assumed power production would be 53% of theoretical maximum. Adjusting for assumed power production, and the expected lifetime, the GWP of Weinzettel et al's concept comes to 6.1 kg $CO_2$-eq / MWh.

Weinzettel et al. does not separate end-of-life marine operations from recycling, they conclude that the end-of-life scenario reduces GWP by 19% as a result of reuse of materials from the wind turbines. However, comparing the total GWP, the emissions from the end-of-life marine operations from the basecase scenario used in this assessment comes to around 3% of the total GWP from Weinzettel et al.

### 11.7.2 Reimers et al., 2014 [18]

In the LCA of Reimers et al. they study an offshore wind farm consisting of 80 5MW WTGs, and compare them to two smaller on shore wind farms. This wind farm is similar in scope to the wind farms considered in this thesis. They also assume a 20 year life time.

Reimers et al. also expect emissions from decommissioning operations to be the same as for the wind farm assembly. In this paper however, they go into greater detail on the marine operations in the installation phase. They assume a jack up installation vessel is used for a total of 5 days for the installation of both the turbine and foundations, similar to the estimates used in this thesis for monopile and WTG removal and disassembly. However, they do not include the need for a separate barge for transportation, or the use of ROV support vessels prior to commencing removal. Additionally, they assume vessels operate under full load during the entire process. This runs the risk of creating unrealistically high estimations of the energy requirements for the vessels. Still, Reimers et al. assume the use of much smaller vessels than the ones considered in this thesis, presumably due to the age of the paper (2014).

The results from this paper estimates 0.40 kg $CO_2$-eq / MWh for the EoL phase, adjusted for lifetime and rated power production. However, this also includes transportation over land, and the final break up of the WTG components. This result is about twice as high as the results from the base scenario in this thesis. The paper does not comment how much of the GWP related to the EoL scenario comes from the marine operations alone.

### 11.7.3 Bonou et al., 2016 [21]

Bonou et al. compares several different on shore and offshore concepts, the largest of which is an offshore wind turbine rated for 6MW. The life time was assumed as 25 years, same as in this thesis.

The results was a GWP of 4.6 kg $CO_2$-eq / MWh, adjusted for assumed power output in the paper. Of this, 7% are related to disassembly operations, or 0.322 kg $CO_2$-eq / MWh. However, the paper comments that the data quality for the dismantling phase is poor, and that more statistics is needed to find the differences between installation and decommissioning. This paper also assumes dismantling is the same as installation.

## 11.8 Economic Factors/Cost benefits

The cost of decommissioning has been estimated by some to be 3% of the total capital cost of a wind farm project [29]. However, this will naturally depend on the type of wind farm and an array of other different factors.

In general, the emissions found in this analysis, is closely related to vessel time, and the number of vessels involved. The same is the case for the cost of vessels involved.

Typical charter rates for jack up SPIVs can be as high as 125 000 € / day [15, 81], and the average charter rates for AHTSs in the north sea were in September 2020 about 20 000€ / day [82]. A comparison between the base scenario and the scenario where the decommissioning SPIV returns with the foundations is shown in the table below:

Table 23: Cost estimations for barge return and SPIV return solutions for the foundations.

| **Scenario** | **Barge return** | **SPIV return** |
|---|---|---|
| **Total SPIV use** | 302 days | 359 days |
| **Total AHTS use** | 350 days | 0 h |
| **Cost** | 45 m€ | 45 m€ |

The results in Table 23 shows that although installation vessels can be more expensive, the major reduction in use of AHTSs makes the cost for both options practically identical.

The results show that using vessels efficiently is most often both the most environmentally friendly, and costs less.

There are many uncertainties with this cost estimate, as charter rates can vary wildly, and are generally not consistent over longer periods of time, such as the lifetime of an offshore wind farm. In addition, the development of new methods and technologies may further drive down costs in the future, such as vessel like the *Seaway Alfa Lift*, as discussed in Section 10.3. However, some expect the large amount of wind farms that will require decommissioning in the near future will massively increase demands, and consequently also cost associated with vessel charter [23].

# 12 Conclusion

The stated goal of this thesis, as explained in Section 8, was to compare how different EoL scenarios for offshore wind farms affect the environmental impact of marine operations related to decommissioning. Several different wind farms and scenarios were developed, in order to identify what factors had the biggest effect on the global warming potential.

For the basecase, of an entirely "average" wind farm consisting of 100 8 MW WTGs, the GWP was found to be 0.16 kg $CO_2$-eq / MWh. This result is slightly lower than other estimates for EoL found in literature. However, it was found that it was possible to further reduce the GWP, using new techniques for transportation when dismantling the foundations, or by increasing the size of the offshore wind turbines.

The biggest differences in GWP however, was found to be between wind farms using different foundations. The heavy and cumbersome GBF and jacket foundations are increase the amount of both time and necessary vessels in order to complete the decommissioning of the wind farm.

The results show that in order to reduce the environmental impact from offshore wind decommissioning, wind farm operators should strive to make transportation more efficient, reduce the number of vessels necessary to execute the decommissioning, and build larger wind farms, both in number of turbines, and in each individual turbines rated power production.

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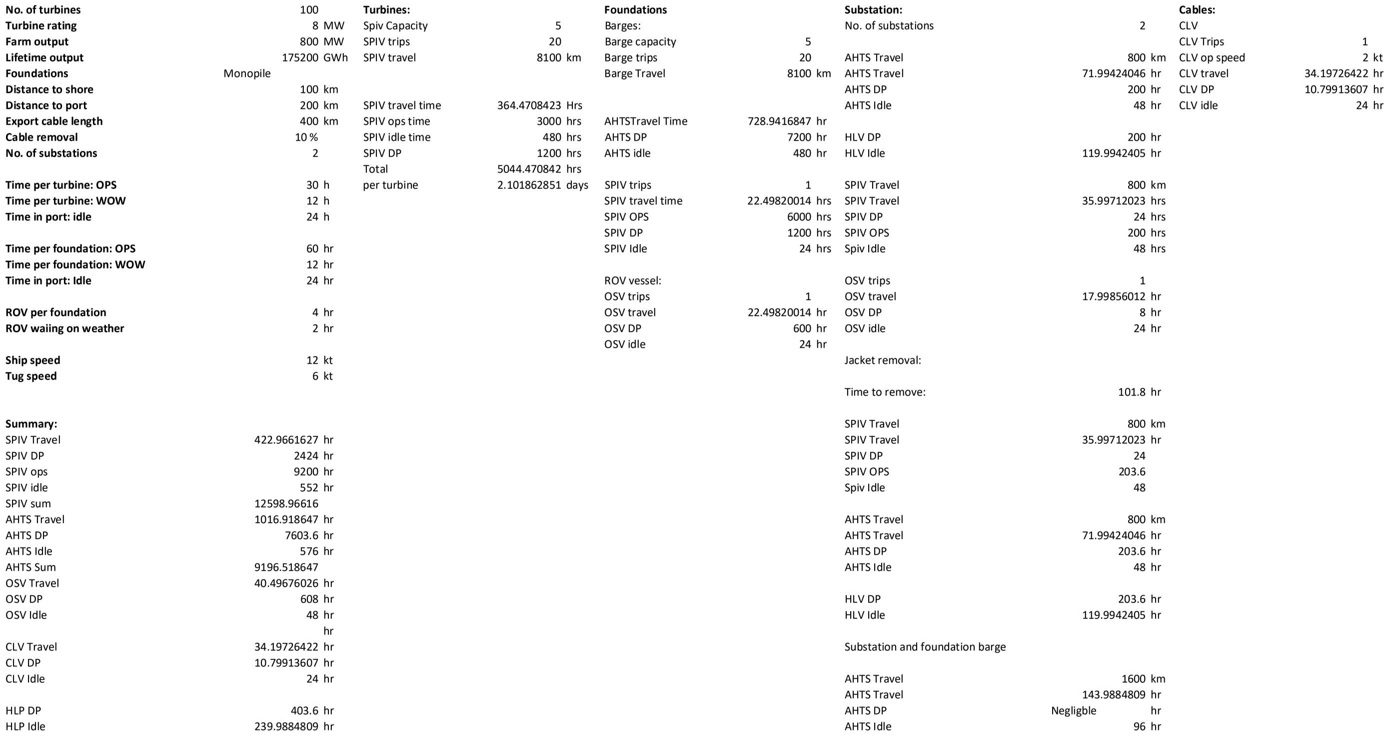
# Appendix

## A Base case



| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 100 | | **Turbines:** | | | **Foundations** | | | **Substation:** | | | **Cables:** | | |
| **Turbine rating** | 8 | MW | Spiv Capacity | 5 | | Barges: | | | No. of substations | 2 | | CLV | | |
| **Farm output** | 800 | MW | SPIV trips | 20 | | Barge capacity | 5 | | | | | CLV Trips | 1 | |
| **Lifetime output** | 175200 | GWh | SPIV travel | 8100 | km | Barge trips | 20 | | AHTS Travel | 800 | km | CLV op speed | 2 | kt |
| **Foundations** | Monopile | | | | | Barge Travel | 8100 | km | AHTS Travel | 71.99424046 | hr | CLV travel | 34.19726422 | hr |
| **Distance to shore** | 100 | km | | | | | | | AHTS DP | 200 | hr | CLV DP | 10.79913607 | hr |
| **Distance to port** | 200 | km | SPIV travel time | 364.4708423 | Hrs | | | | AHTS Idle | 48 | hr | CLV idle | 24 | hr |
| **Export cable length** | 400 | km | SPIV ops time | 3000 | hrs | AHTSTravel Time | 728.9416847 | hr | | | | | | |
| **Cable removal** | 10 | % | SPIV idle time | 480 | hrs | AHTS DP | 7200 | hr | HLV DP | 200 | hr | | | |
| **No. of substations** | 2 | | SPIV DP | 1200 | hrs | AHTS idle | 480 | hr | HLV Idle | 119.9942405 | hr | | | |
| | | | Total | 5044.470842 | hrs | | | | | | | | | |
| **Time per turbine: OPS** | 30 | h | per turbine | 2.101862851 | days | SPIV trips | 1 | | SPIV Travel | 800 | km | | | |
| **Time per turbine: WOW** | 12 | h | | | | SPIV travel time | 22.49820014 | hrs | SPIV Travel | 35.99712023 | hrs | | | |
| **Time in port: idle** | 24 | h | | | | SPIV OPS | 6000 | hrs | SPIV DP | 24 | hrs | | | |
| | | | | | | SPIV DP | 1200 | hrs | SPIV OPS | 200 | hrs | | | |
| **Time per foundation: OPS** | 60 | hr | | | | SPIV Idle | 24 | hrs | Spiv Idle | 48 | hrs | | | |
| **Time per foundation: WOW** | 12 | hr | | | | | | | | | | | | |
| **Time in port: Idle** | 24 | hr | | | | ROV vessel: | | | OSV trips | 1 | | | | |
| | | | | | | OSV trips | 1 | | OSV travel | 17.99856012 | hr | | | |
| **ROV per foundation** | 4 | hr | | | | OSV travel | 22.49820014 | hr | OSV DP | 8 | hr | | | |
| **ROV waiing on weather** | 2 | hr | | | | OSV DP | 600 | hr | OSV idle | 24 | hr | | | |
| | | | | | | OSV idle | 24 | hr | | | | | | |
| **Ship speed** | 12 | kt | | | | | | | Jacket removal: | | | | | |
| **Tug speed** | 6 | kt | | | | | | | | | | | | |
| | | | | | | | | | Time to remove: | 101.8 | hr | | | |
| **Summary:** | | | | | | | | | SPIV Travel | 800 | km | | | |
| SPIV Travel | 422.9661627 | hr | | | | | | | SPIV Travel | 35.99712023 | hr | | | |
| SPIV DP | 2424 | hr | | | | | | | SPIV DP | 24 | | | | |
| SPIV ops | 9200 | hr | | | | | | | SPIV OPS | 203.6 | | | | |
| SPIV idle | 552 | hr | | | | | | | Spiv Idle | 48 | | | | |
| SPIV sum | 12598.96616 | | | | | | | | | | | | | |
| AHTS Travel | 1016.918647 | hr | | | | | | | AHTS Travel | 800 | km | | | |
| AHTS DP | 7603.6 | hr | | | | | | | AHTS Travel | 71.99424046 | hr | | | |
| AHTS Idle | 576 | hr | | | | | | | AHTS DP | 203.6 | hr | | | |
| AHTS Sum | 9196.518647 | | | | | | | | AHTS Idle | 48 | hr | | | |
| OSV Travel | 40.49676026 | hr | | | | | | | | | | | | |
| OSV DP | 608 | hr | | | | | | | HLV DP | 203.6 | hr | | | |
| OSV Idle | 48 | hr | | | | | | | HLV Idle | 119.9942405 | hr | | | |
| | | hr | | | | | | | | | | | | |
| CLV Travel | 34.19726422 | hr | | | | | | | Substation and foundation barge | | | | | |
| CLV DP | 10.79913607 | hr | | | | | | | | | | | | |
| CLV Idle | 24 | hr | | | | | | | AHTS Travel | 1600 | km | | | |
| | | | | | | | | | AHTS Travel | 143.9884809 | hr | | | |
| HLP DP | 403.6 | hr | | | | | | | AHTS DP | Negligble | hr | | | |
| HLP Idle | 239.9884809 | hr | | | | | | | AHTS Idle | 96 | hr | | | |

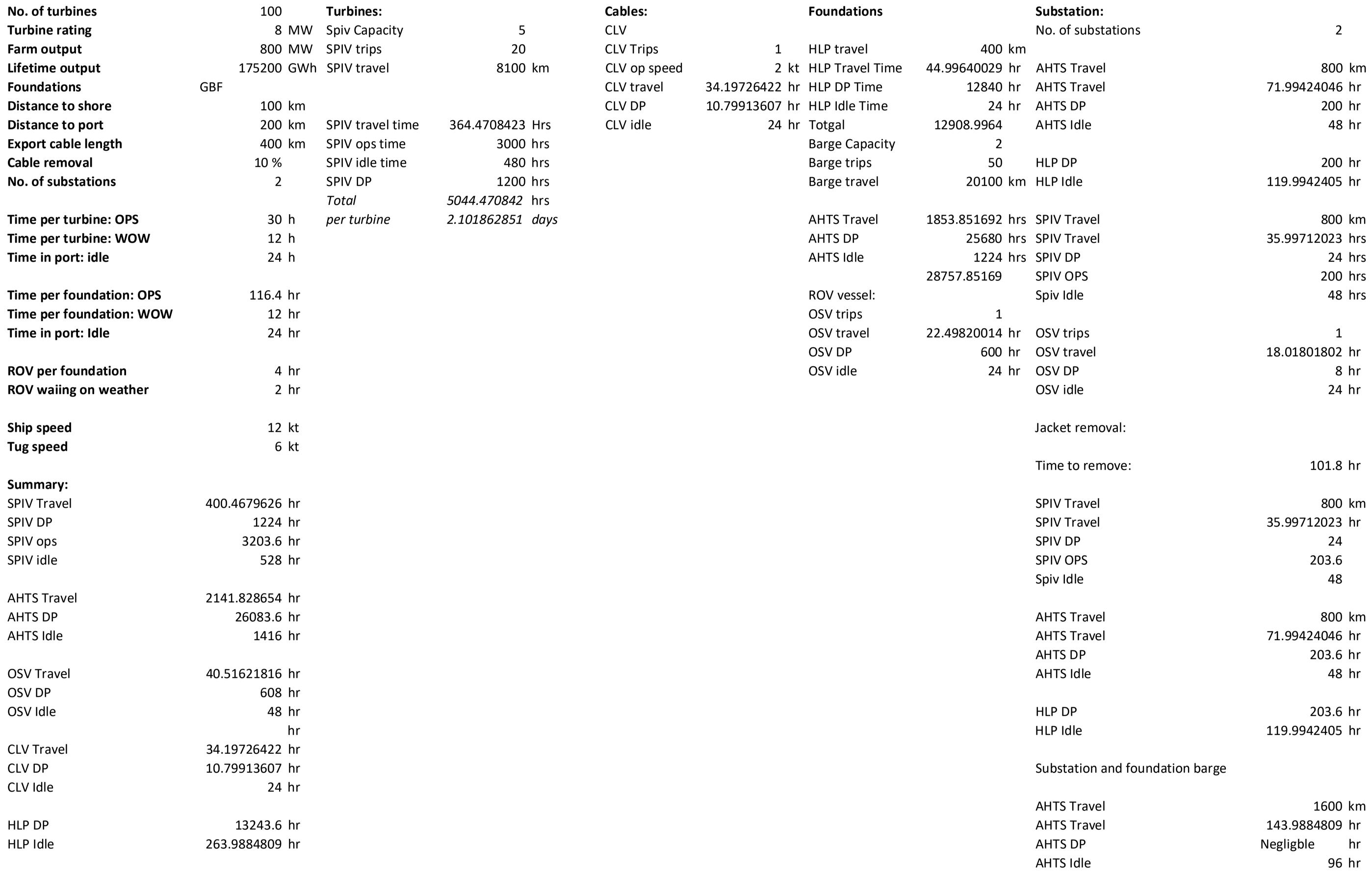
## A.1 Retrun foundations on SPIV

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 100 | | **Turbines:** | | | **Cabels:** | | | **Foundations** | | | **Substation:** | | |
| **Turbine rating** | 8 | MW | Spiv Capacity | 5 | | CLV | | | SPIV Capacity | 3 | | No. of substations | 2 | |
| **Farm output** | 800 | MW | SPIV trips | 20 | | CLV Trips | 1 | | SPIV trips | 34 | | | | |
| **Lifetime output** | 175200 | GWh | SPIV travel | 8100 | km | CLV op speed | 2 | kt | SPIV travel time | 616.4506839 | hrs | AHTS Travel | 800 | km |
| **Foundations** | Monopile | | | | | CLV travel | 34.19726422 | hr | SPIV OPS | 6000 | hrs | AHTS Travel | 71.99424046 | hr |
| **Distance to shore** | 100 | km | | | | CLV DP | 10.79913607 | hr | SPIV DP | 1200 | hrs | AHTS DP | 200 | hr |
| **Distance to port** | 200 | km | SPIV travel time | 364.4708423 | Hrs | CLV idle | 24 | hr | SPIV Idle | 816 | hrs | AHTS Idle | 48 | hr |
| **Export cable length** | 400 | km | SPIV ops time | 3000 | hrs | | | | Total | 8632.450684 | | | | |
| **Cable removal** | 10 | % | SPIV idle time | 480 | hrs | | | | ROV vessel: | | | HLV DP | 200 | hr |
| **No. of substations** | 2 | | SPIV DP | 1200 | hrs | | | | OSV trips | 1 | | HLV Idle | 119.9942405 | hr |
| | | | Total | 5044.470842 | hrs | | | | OSV travel | 22.49820014 | hr | | | |
| **Time per turbine: OPS** | 30 | hr | per turbine | 2.101862851 | days | | | | OSV DP | 600 | hr | SPIV Travel | 800 | km |
| **Time per turbine: WOW** | 12 | hr | | | | | | | OSV idle | 24 | hr | SPIV Travel | 35.99712023 | hrs |
| **Time in port: idle** | 24 | hr | | | | | | | | | | SPIV DP | 24 | hrs |
| | | | | | | | | | | | | SPIV OPS | 200 | hrs |
| **Time per foundation: OPS** | 60 | hr | | | | | | | | | | Spiv Idle | 48 | hrs |
| **Time per foundation: WOW** | 12 | hr | | | | | | | | | | | | |
| **Time in port: Idle** | 24 | hr | | | | | | | | | | OSV trips | 1 | |
| | | | | | | | | | | | | OSV travel | 17.99856012 | hr |
| **ROV per foundation** | 4 | hr | | | | | | | | | | OSV DP | 8 | hr |
| **ROV waiing on weather** | 2 | hr | | | | | | | | | | OSV idle | 24 | hr |
| **Ship speed** | 12 | kt | | | | | | | | | | Jacket removal: | | |
| **Tug speed** | 6 | kt | | | | | | | | | | | | |
| | | | | | | | | | | | | Time to remove: | 101.8 | hr |
| **Summary:** | | | | | | | | | | | | | | |
| *SPIV Travel* | 1016.918647 | hr | | | | | | | | | | SPIV Travel | 800 | km |
| *SPIV DP* | 2424 | hr | | | | | | | | | | SPIV Travel | 35.99712023 | hr |
| *SPIV ops* | 9200 | hr | | | | | | | | | | SPIV DP | 24 | |
| *SPIV idle* | 1344 | hr | | | | | | | | | | SPIV OPS | 203.6 | |
| Sum SPIV | 13984.91865 | | | | | | | | | | | Spiv Idle | 48 | |
| *AHTS Travel* | 287.9769618 | hr | | | | | | | | | | | | |
| *AHTS DP* | 403.6 | hr | | | | | | | | | | AHTS Travel | 800 | km |
| *AHTS Idle* | 192 | hr | | | | | | | | | | AHTS Travel | 71.99424046 | hr |
| *Sum AHTS* | 883.5769618 | | | | | | | | | | | AHTS DP | 203.6 | hr |
| *OSV Travel* | 40.49676026 | hr | | | | | | | | | | AHTS Idle | 48 | hr |
| *OSV DP* | 608 | hr | | | | | | | | | | | | |
| *OSV Idle* | 48 | hr | | | | | | | | | | HLP DP | 203.6 | hr |
| | | | | | | | | | | | | HLP Idle | 119.9942405 | hr |
| *CLV Travel* | 34.19726422 | hr | | | | | | | | | | | | |
| *CLV DP* | 10.79913607 | hr | | | | | | | | | | Substation and foundation barge | | |
| *CLV Idle* | 24 | hr | | | | | | | | | | | | |
| | | | | | | | | | | | | AHTS Travel | 1600 | km |
| *HLP DP* | 403.6 | hr | | | | | | | | | | AHTS Travel | 143.9884809 | hr |
| *HLP Idle* | 239.9884809 | hr | | | | | | | | | | AHTS DP | Negligble | hr |
| | | | | | | | | | | | | AHTS Idle | 96 | hr |

## B 200 km from shore

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 100 | | **Turbines:** | | | **Cables:** | | | **Foundations** | | | **Substation:** | | |
| **Turbine rating** | 8 | MW | Spiv Capacity | 5 | | CLV | | | Barges: | | | No. of substations | 2 | |
| **Farm output** | 800 | MW | SPIV trips | 20 | | CLV Trips | 1 | | Barge capacity | 5 | | | | |
| **Lifetime output** | 175200 | GWh | SPIV travel | 12100 | km | CLV op speed | 2 | kt | Barge trips | 20 | | AHTS Travel | 1200 | km |
| **Foundations** | Monopile | | | | | CLV travel | 68.39452844 | hr | Barge Travel | 12100 | km | AHTS Travel | 107.9913607 | hr |
| **Distance to shore** | 200 | km | | | | CLV DP | 21.59827214 | hr | | | | AHTS DP | 200 | hr |
| **Distance to port** | 300 | km | SPIV travel time | 544.4564435 | Hrs | CLV idle | 24 | hr | AHTS/Barge Travel Time | 1088.912887 | hr | AHTS Idle | 48 | hr |
| **Export cable length** | 800 | km | SPIV ops time | 3000 | hrs | | | | AHTS DP | 7200 | hr | | | |
| **Cable removal** | 10 | % | SPIV idle time | 480 | hrs | | | | AHTS idle | 480 | hr | HLV DP | 200 | hr |
| **No. of substations** | 2 | | SPIV DP | 1200 | hrs | | | | | | | HLV Idle | 155.9913607 | hr |
| | | | Total | 5224.456443 | hrs | | | | SPIV trips | 1 | | | | |
| **Time per turbine: OPS** | 30 | h | per turbine | 2.176856851 | days | | | | SPIV travel time | 31.4974802 | hrs | SPIV Travel | 1200 | km |
| **Time per turbine: WOW** | 12 | h | | | | | | | SPIV OPS | 6000 | hrs | SPIV Travel | 53.99568035 | hrs |
| **Time in port: idle** | 24 | h | | | | | | | SPIV DP | 1200 | hrs | SPIV DP | 24 | hrs |
| | | | | | | | | | SPIV Idle | 24 | hrs | SPIV OPS | 200 | hrs |
| **Time per foundation: OPS** | 60 | hr | | | | | | | | | | Spiv Idle | 48 | hrs |
| **Time per foundation: WOW** | 12 | hr | | | | | | | ROV vessel: | | | | | |
| **Time in port: Idle** | 24 | hr | | | | | | | OSV trips | 1 | | OSV trips | 1 | |
| | | | | | | | | | OSV travel | 31.4974802 | hr | OSV travel | 26.99784017 | hr |
| **ROV per foundation** | 4 | hr | | | | | | | OSV DP | 600 | hr | OSV DP | 8 | hr |
| **ROV waiing on weather** | 2 | hr | | | | | | | OSV idle | 24 | hr | OSV idle | 24 | hr |
| **Ship speed** | 12 | kt | | | | | | | | | | Jacket removal: | | |
| **Tug speed** | 6 | kt | | | | | | | | | | | | |
| | | | | | | | | | | | | Time to remove: | 101.8 | hr |
| **Summary:** | | | | | | | | | | | | | | |
| SPIV Travel | 629.949604 | hr | | | | | | | | | | SPIV Travel | 1200 | km |
| SPIV DP | 2424 | hr | | | | | | | | | | SPIV Travel | 53.99568035 | hr |
| SPIV ops | 9200 | hr | | | | | | | | | | SPIV DP | 24 | |
| SPIV idle | 552 | hr | | | | | | | | | | SPIV OPS | 203.6 | |
| | 12805.9496 | | | | | | | | | | | Spiv Idle | 48 | |
| AHTS Travel | 1520.87833 | hr | | | | | | | | | | | | |
| AHTS DP | 7603.6 | hr | | | | | | | | | | AHTS Travel | 1200 | km |
| AHTS Idle | 576 | hr | | | | | | | | | | AHTS Travel | 107.9913607 | hr |
| | | | | | | | | | | | | AHTS DP | 203.6 | hr |
| OSV Travel | 58.49532037 | hr | | | | | | | | | | AHTS Idle | 48 | hr |
| OSV DP | 608 | hr | | | | | | | | | | | | |
| OSV Idle | 48 | hr | | | | | | | | | | HLV DP | 203.6 | hr |
| | | hr | | | | | | | | | | HLV Idle | 155.9913607 | hr |
| CLV Travel | 68.39452844 | hr | | | | | | | | | | | | |
| CLV DP | 21.59827214 | hr | | | | | | | | | | Substation and foundation barge | | |
| CLV Idle | 24 | hr | | | | | | | | | | | | |
| | | | | | | | | | | | | AHTS Travel | 2400 | km |
| HLV DP | 403.6 | hr | | | | | | | | | | AHTS Travel | 215.9827214 | hr |
| HLV Idle | 311.9827214 | hr | | | | | | | | | | AHTS DP | Negligble | hr |
| | | | | | | | | | | | | AHTS Idle | 96 | hr |

## C GBF wind farm



| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 100 | | **Turbines:** | | | **Cables:** | | | **Foundations** | | | **Substation:** | | |
| **Turbine rating** | 8 | MW | Spiv Capacity | 5 | | CLV | | | | | | No. of substations | 2 | |
| **Farm output** | 800 | MW | SPIV trips | 20 | | CLV Trips | 1 | | HLP travel | 400 | km | | | |
| **Lifetime output** | 175200 | GWh | SPIV travel | 8100 | km | CLV op speed | 2 | kt | HLP Travel Time | 44.99640029 | hr | AHTS Travel | 800 | km |
| **Foundations** | GBF | | | | | CLV travel | 34.19726422 | hr | HLP DP Time | 12840 | hr | AHTS Travel | 71.99424046 | hr |
| **Distance to shore** | 100 | km | | | | CLV DP | 10.79913607 | hr | HLP Idle Time | 24 | hr | AHTS DP | 200 | hr |
| **Distance to port** | 200 | km | SPIV travel time | 364.4708423 | Hrs | CLV idle | 24 | hr | Totgal | 12908.9964 | | AHTS Idle | 48 | hr |
| **Export cable length** | 400 | km | SPIV ops time | 3000 | hrs | | | | Barge Capacity | 2 | | | | |
| **Cable removal** | 10 | % | SPIV idle time | 480 | hrs | | | | Barge trips | 50 | | HLP DP | 200 | hr |
| **No. of substations** | 2 | | SPIV DP | 1200 | hrs | | | | Barge travel | 20100 | km | HLP Idle | 119.9942405 | hr |
| | | | *Total* | *5044.470842* | *hrs* | | | | | | | | | |
| **Time per turbine: OPS** | 30 | h | *per turbine* | *2.101862851* | *days* | | | | AHTS Travel | 1853.851692 | hrs | SPIV Travel | 800 | km |
| **Time per turbine: WOW** | 12 | h | | | | | | | AHTS DP | 25680 | hrs | SPIV Travel | 35.99712023 | hrs |
| **Time in port: idle** | 24 | h | | | | | | | AHTS Idle | 1224 | hrs | SPIV DP | 24 | hrs |
| | | | | | | | | | | 28757.85169 | | SPIV OPS | 200 | hrs |
| **Time per foundation: OPS** | 116.4 | hr | | | | | | | ROV vessel: | | | Spiv Idle | 48 | hrs |
| **Time per foundation: WOW** | 12 | hr | | | | | | | OSV trips | 1 | | | | |
| **Time in port: Idle** | 24 | hr | | | | | | | OSV travel | 22.49820014 | hr | OSV trips | 1 | |
| | | | | | | | | | OSV DP | 600 | hr | OSV travel | 18.01801802 | hr |
| **ROV per foundation** | 4 | hr | | | | | | | OSV idle | 24 | hr | OSV DP | 8 | hr |
| **ROV waiing on weather** | 2 | hr | | | | | | | | | | OSV idle | 24 | hr |
| **Ship speed** | 12 | kt | | | | | | | | | | Jacket removal: | | |
| **Tug speed** | 6 | kt | | | | | | | | | | | | |
| | | | | | | | | | | | | Time to remove: | 101.8 | hr |
| **Summary:** | | | | | | | | | | | | | | |
| SPIV Travel | 400.4679626 | hr | | | | | | | | | | SPIV Travel | 800 | km |
| SPIV DP | 1224 | hr | | | | | | | | | | SPIV Travel | 35.99712023 | hr |
| SPIV ops | 3203.6 | hr | | | | | | | | | | SPIV DP | 24 | |
| SPIV idle | 528 | hr | | | | | | | | | | SPIV OPS | 203.6 | |
| | | | | | | | | | | | | Spiv Idle | 48 | |
| AHTS Travel | 2141.828654 | hr | | | | | | | | | | | | |
| AHTS DP | 26083.6 | hr | | | | | | | | | | AHTS Travel | 800 | km |
| AHTS Idle | 1416 | hr | | | | | | | | | | AHTS Travel | 71.99424046 | hr |
| | | | | | | | | | | | | AHTS DP | 203.6 | hr |
| OSV Travel | 40.51621816 | hr | | | | | | | | | | AHTS Idle | 48 | hr |
| OSV DP | 608 | hr | | | | | | | | | | | | |
| OSV Idle | 48 | hr | | | | | | | | | | HLP DP | 203.6 | hr |
| | | hr | | | | | | | | | | HLP Idle | 119.9942405 | hr |
| CLV Travel | 34.19726422 | hr | | | | | | | | | | | | |
| CLV DP | 10.79913607 | hr | | | | | | | | | | Substation and foundation barge | | |
| CLV Idle | 24 | hr | | | | | | | | | | | | |
| | | | | | | | | | | | | AHTS Travel | 1600 | km |
| HLP DP | 13243.6 | hr | | | | | | | | | | AHTS Travel | 143.9884809 | hr |
| HLP Idle | 263.9884809 | hr | | | | | | | | | | AHTS DP | Negligble | hr |
| | | | | | | | | | | | | AHTS Idle | 96 | hr |

## C.1 GBF, new vessel

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 100 | | **Turbines:** | | | **Cables:** | | | **Foundations** | | | **Substation:** | | |
| **Turbine rating** | 8 | MW | Spiv Capacity | 5 | | CLV | | | | | | No. of substations | 2 | |
| **Farm output** | 800 | MW | SPIV trips | 20 | | CLV Trips | 1 | | Large HLV: | | | | | |
| **Lifetime output** | 175200 | GWh | SPIV travel | 8100 | km | CLV op speed | 2 | kt | HLV Capacity | 5 | | AHTS Travel | 800 | km |
| **Foundations** | GBF | | | | | CLV travel | 34.19726422 | hr | HLV trips | 20 | | AHTS Travel | 71.99424046 | hr |
| **Distance to shore** | 100 | km | | | | CLV DP | 10.79913607 | hr | HLV travel | 8100 | km | AHTS DP | 200 | hr |
| **Distance to port** | 200 | km | SPIV travel time | 364.4708423 | Hrs | CLV idle | 24 | hr | | | | AHTS Idle | 48 | hr |
| **Export cable length** | 400 | km | SPIV ops time | 3000 | hrs | | | | HLV Travel Time | 364.4708423 | hr | | | |
| **Cable removal** | 10 | % | SPIV idle time | 480 | hrs | | | | HLV DP Time | 12840 | hr | HLP DP | 200 | hr |
| **No. of substations** | 2 | | SPIV DP | 1200 | hrs | | | | HLV Idle Time | 480 | hr | HLP Idle | 119.9942405 | hr |
| | | | Total | 5044.470842 | hrs | | | | | | | | | |
| **Time per turbine: OPS** | 30 | h | per turbine | 2.101862851 | days | | | | ROV vessel: | | | SPIV Travel | 800 | km |
| **Time per turbine: WOW** | 12 | h | | | | | | | OSV trips | 1 | | SPIV Travel | 35.99712023 | hrs |
| **Time in port: idle** | 24 | h | | | | | | | OSV travel | 22.49820014 | hr | SPIV DP | 24 | hrs |
| | | | | | | | | | OSV DP | 600 | hr | SPIV OPS | 200 | hrs |
| **Time per foundation: OPS** | 116.4 | hr | | | | | | | OSV idle | 24 | hr | Spiv Idle | 48 | hrs |
| **Time per foundation: WOW** | 12 | hr | | | | | | | | | | | | |
| **Time in port: Idle** | 24 | hr | | | | | | | | | | OSV trips | 1 | |
| | | | | | | | | | | | | OSV travel | 18.01801802 | hr |
| **ROV per foundation** | 4 | hr | | | | | | | | | | OSV DP | 8 | hr |
| **ROV waiing on weather** | 2 | hr | | | | | | | | | | OSV idle | 24 | hr |
| | | | | | | | | | | | | | | |
| **Ship speed** | 12 | kt | | | | | | | | | | Jacket removal: | | |
| **Tug speed** | 6 | kt | | | | | | | | | | | | |
| | | | | | | | | | | | | Time to remove: | 101.8 | hr |
| **Summary:** | | | | | | | | | | | | | | |
| SPIV Travel | 400.4679626 | hr | | | | | | | | | | SPIV Travel | 800 | km |
| SPIV DP | 1224 | hr | | | | | | | | | | SPIV Travel | 35.99712023 | hr |
| SPIV ops | 3203.6 | hr | | | | | | | | | | SPIV DP | 24 | |
| SPIV idle | 528 | hr | | | | | | | | | | SPIV OPS | 203.6 | |
| | | | | | | | | | | | | Spiv Idle | 48 | |
| AHTS Travel | 287.9769618 | hr | | | | | | | | | | | | |
| AHTS DP | 403.6 | hr | | | | | | | | | | AHTS Travel | 800 | km |
| AHTS Idle | 192 | hr | | | | | | | | | | AHTS Travel | 71.99424046 | hr |
| | | | | | | | | | | | | AHTS DP | 203.6 | hr |
| OSV Travel | 40.51621816 | hr | | | | | | | | | | AHTS Idle | 48 | hr |
| OSV DP | 608 | hr | | | | | | | | | | | | |
| OSV Idle | 48 | hr | | | | | | | | | | HLP DP | 203.6 | hr |
| | | hr | | | | | | | | | | HLP Idle | 119.9942405 | hr |
| CLV Travel | 34.19726422 | hr | | | | | | | | | | | | |
| CLV DP | 10.79913607 | hr | | | | | | | | | | Substation and foundation barge | | |
| CLV Idle | 24 | hr | | | | | | | | | | | | |
| | | | | | | | | | | | | AHTS Travel | 1600 | km |
| HLP DP | 403.6 | hr | | | | | | | | | | AHTS Travel | 143.9884809 | hr |
| HLP Idle | 239.9884809 | hr | | | | | | | | | | AHTS DP | Negligble | hr |
| | | | | | | | | | | | | AHTS Idle | 96 | hr |
| HLV Travel | 364.4708423 | hr | | | | | | | | | | | | |
| HLV DP | 12840 | hr | | | | | | | | | | | | |
| HLV Idle | 480 | hr | | | | | | | | | | | | |

# D Jacket wind farm

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 100 | | **Turbines:** | | | **Cables** | | | **Foundations** | | | **Substation:** | | |
| **Turbine rating** | 8 | MW | Spiv Capacity | 5 | | CLV | | | | | | No. of substations | 2 | |
| **Farm output** | 800 | MW | SPIV trips | 20 | | CLV Trips | 1 | | HLP travel | 400 | km | | | |
| **Lifetime output** | 175200 | GWh | SPIV travel | 8100 | km | CLV op speed | 2 | kt | HLP Travel Time | 44.99640029 | hr | AHTS Travel | 800 | km |
| **Foundations** | GBF | | | | | CLV travel | 34.19726422 | hr | HLP DP Time | 12840 | hr | AHTS Travel | 71.99424046 | hr |
| **Distance to shore** | 100 | km | | | | CLV DP | 10.79913607 | hr | HLP Idle Time | 24 | hr | AHTS DP | 200 | hr |
| **Distance to port** | 200 | km | SPIV travel time | 364.4708423 | Hrs | CLV idle | 24 | hr | Total | 12908.9964 | | AHTS Idle | 48 | hr |
| **Export cable length** | 400 | km | SPIV ops time | 3000 | hrs | | | | Barge Capacity | 3 | | | | |
| **Cable removal** | 10 | % | SPIV idle time | 480 | hrs | | | | Barge trips | 34 | | HLP DP | 200 | hr |
| **No. of substations** | 2 | | SPIV DP | 1200 | hrs | | | | Barge travel | 13700 | km | HLP Idle | 119.9942405 | hr |
| | | | *Total* | *5044.470842* | hrs | | | | | | | | | |
| **Time per turbine: OPS** | 30 | h | *per turbine* | *2.101862851* | *days* | | | | AHTS Travel | 1277.897768 | hrs | SPIV Travel | 800 | km |
| **Time per turbine: WOW** | 12 | h | | | | | | | AHTS DP | 25680 | hrs | SPIV Travel | 35.99712023 | hrs |
| **Time in port: idle** | 24 | h | | | | | | | AHTS Idle | 840 | hrs | SPIV DP | 24 | hrs |
| | | | | | | | | | total | 27797.89777 | | SPIV OPS | 200 | hrs |
| **Time per foundation: OPS** | 116.4 | hr | | | | | | | ROV vessel: | | | Spiv Idle | 48 | hrs |
| **Time per foundation: WOW** | 12 | hr | | | | | | | OSV trips | 1 | | | | |
| **Time in port: Idle** | 24 | hr | | | | | | | OSV travel | 22.49820014 | hr | OSV trips | 1 | |
| | | | | | | | | | OSV DP | 600 | hr | OSV travel | 18.01801802 | hr |
| **ROV per foundation** | 4 | hr | | | | | | | OSV idle | 24 | hr | OSV DP | 8 | hr |
| **ROV waiing on weather** | 2 | hr | | | | | | | | | | OSV idle | 24 | hr |
| **Ship speed** | 12 | kt | | | | | | | | | | Jacket removal: | | |
| **Tug speed** | 6 | kt | | | | | | | | | | | | |
| | | | | | | | | | | | | Time to remove: | 101.8 | hr |
| **Summary:** | | | | | | | | | | | | | | |
| SPIV Travel | 400.4679626 | hr | | | | | | | | | | SPIV Travel | 800 | km |
| SPIV DP | 1224 | hr | | | | | | | | | | SPIV Travel | 35.99712023 | hr |
| SPIV ops | 3203.6 | hr | | | | | | | | | | SPIV DP | 24 | |
| SPIV idle | 528 | hr | | | | | | | | | | SPIV OPS | 203.6 | |
| | | | | | | | | | | | | Spiv Idle | 48 | |
| AHTS Travel | 1565.87473 | hr | | | | | | | | | | | | |
| AHTS DP | 26083.6 | hr | | | | | | | | | | AHTS Travel | 800 | km |
| AHTS Idle | 1032 | hr | | | | | | | | | | AHTS Travel | 71.99424046 | hr |
| | | | | | | | | | | | | AHTS DP | 203.6 | hr |
| OSV Travel | 40.51621816 | hr | | | | | | | | | | AHTS Idle | 48 | hr |
| OSV DP | 608 | hr | | | | | | | | | | | | |
| OSV Idle | 48 | hr | | | | | | | | | | HLP DP | 203.6 | hr |
| | | hr | | | | | | | | | | HLP Idle | 119.9942405 | hr |
| CLV Travel | 34.19726422 | hr | | | | | | | | | | | | |
| CLV DP | 10.79913607 | hr | | | | | | | | | | Substation and foundation barge | | |
| CLV Idle | 24 | hr | | | | | | | | | | | | |
| | | | | | | | | | | | | AHTS Travel | 1600 | km |
| HLP DP | 13243.6 | hr | | | | | | | | | | AHTS Travel | 143.9884809 | hr |
| HLP Idle | 263.9884809 | hr | | | | | | | | | | AHTS DP | Negligble | hr |
| | | | | | | | | | | | | AHTS Idle | 96 | hr |

## D.1 jacket, new vessel

| | | |
|---|---|---|
| **No. of turbines** | 100 | |
| **Turbine rating** | 8 | MW |
| **Farm output** | 800 | MW |
| **Lifetime output** | 175200 | GWh |
| **Foundations** | GBF | |
| **Distance to shore** | 100 | km |
| **Distance to port** | 200 | km |
| **Export cable length** | 400 | km |
| **Cable removal** | 10 % | |
| **No. of substations** | 2 | |
| | | |
| **Time per turbine: OPS** | 30 | h |
| **Time per turbine: WOW** | 12 | h |
| **Time in port: idle** | 24 | h |
| | | |
| **Time per foundation: OPS** | 116.4 | hr |
| **Time per foundation: WOW** | 12 | hr |
| **Time in port: Idle** | 24 | hr |
| | | |
| **ROV per foundation** | 4 | hr |
| **ROV waiing on weather** | 2 | hr |
| | | |
| **Ship speed** | 12 | kt |
| **Tug speed** | 6 | kt |
| | | |
| **Summary:** | | |
| SPIV Travel | 400.4679626 | hr |
| SPIV DP | 1224 | hr |
| SPIV ops | 3203.6 | hr |
| SPIV idle | 528 | hr |
| | | |
| AHTS Travel | 287.9769618 | hr |
| AHTS DP | 403.6 | hr |
| AHTS Idle | 192 | hr |
| hr | | |
| OSV Travel | 40.51621816 | hr |
| OSV DP | 608 | |
| OSV Idle | 48 | hr |
| | | hr |
| CLV Travel | 34.19726422 | hr |
| CLV DP | 10.79913607 | hr |
| CLV Idle | 24 | hr |
| | | |
| HLP DP | 403.6 | hr |
| HLP Idle | 239.9884809 | hr |
| | | |
| HLV Travel | 238.4809215 | hr |
| HLV DP | 12840 | hr |
| HLV Idle | 312 | hr |

| | | |
|---|---|---|
| **Turbines:** | | |
| Spiv Capacity | 5 | |
| SPIV trips | 20 | |
| SPIV travel | 8100 | km |
| | | |
| | | |
| SPIV travel time | 364.4708423 | Hrs |
| SPIV ops time | 3000 | hrs |
| SPIV idle time | 480 | hrs |
| SPIV DP | 1200 | hrs |
| *Total* | *5044.470842* | hrs |
| *per turbine* | *2.101862851* | *days* |

| | | |
|---|---|---|
| **Cables:** | | |
| CLV | | |
| CLV Trips | 1 | |
| CLV op speed | 2 | kt |
| CLV travel | 34.19726422 | hr |
| CLV DP | 10.79913607 | hr |
| CLV idle | 24 | hr |

| | | |
|---|---|---|
| **Foundations** | | |
| | | |
| Large HLV: | | |
| HLV Capacity | 8 | |
| HLV trips | 13 | |
| HLV travel | 5300 | km |
| | | |
| HLV Travel Time | 238.4809215 | hr |
| HLV DP Time | 12840 | hr |
| HLV Idle Time | 312 | hr |
| | | |
| ROV vessel: | | |
| OSV trips | 1 | |
| OSV travel | 22.49820014 | hr |
| OSV DP | 600 | hr |
| OSV idle | 24 | hr |

| | | |
|---|---|---|
| **Substation:** | | |
| No. of substations | 2 | |
| | | |
| AHTS Travel | 800 | km |
| AHTS Travel | 71.99424046 | hr |
| AHTS DP | 200 | hr |
| AHTS Idle | 48 | hr |
| | | |
| HLP DP | 200 | hr |
| HLP Idle | 119.9942405 | hr |
| | | |
| SPIV Travel | 800 | km |
| SPIV Travel | 35.99712023 | hrs |
| SPIV DP | 24 | hrs |
| SPIV OPS | 200 | hrs |
| Spiv Idle | 48 | hrs |
| | | |
| OSV trips | 1 | |
| OSV travel | 18.01801802 | hr |
| OSV DP | 8 | hr |
| OSV idle | 24 | hr |
| | | |
| Jacket removal: | | |
| | | |
| Time to remove: | 101.8 | hr |
| | | |
| SPIV Travel | 800 | km |
| SPIV Travel | 35.99712023 | hr |
| SPIV DP | 24 | |
| SPIV OPS | 203.6 | |
| Spiv Idle | 48 | |
| | | |
| AHTS Travel | 800 | km |
| AHTS Travel | 71.99424046 | hr |
| AHTS DP | 203.6 | hr |
| AHTS Idle | 48 | hr |
| | | |
| HLP DP | 203.6 | hr |
| HLP Idle | 119.9942405 | hr |
| | | |
| Substation and foundation barge | | |
| | | |
| AHTS Travel | 1600 | km |
| AHTS Travel | 143.9884809 | hr |
| AHTS DP | Negligble | hr |
| AHTS Idle | 96 | hr |

# E 4 MW windfarm

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 200 | **Turbines:** | | **Cables** | | **Foundations** | | **Substation:** | |
| **Turbine rating** | 4 MW | Spiv Capacity | 8 | CLV | | Barges: | | No. of substations | 2 |
| **Farm output** | 800 MW | SPIV trips | 25 | CLV Trips | 1 | Barge capacity | 8 | | |
| **Lifetime output** | 175200 GWh | SPIV travel | 10200 km | CLV op speed | 2 kt | Barge trips | 25 | AHTS Travel | 800 km |
| **Foundations** | Monopile | | | CLV travel | 34.19726422 hr | Barge Travel | 10200 km | AHTS Travel | 71.99424046 hr |
| **Distance to shore** | 100 km | | | CLV DP | 10.79913607 hr | | | AHTS DP | 200 hr |
| **Distance to port** | 200 km | SPIV travel time | 458.9632829 Hrs | CLV idle | 24 hr | | | AHTS Idle | 48 hr |
| **Export cable length** | 400 km | SPIV ops time | 6000 hrs | | | AHTS/Barge Travel Time | 917.9265659 hr | | |
| **Cable removal** | 10 % | SPIV idle time | 600 hrs | | | AHTS DP | 14400 hr | HLV DP | 200 hr |
| **No. of substations** | 2 | SPIV DP | 2400 hrs | | | AHTS idle | 600 hr | HLV Idle | 119.9942405 hr |
| | | *Total* | *9458.963283 hrs* | | | | | | |
| **Time per turbine: OPS** | 30 h | *per turbine* | *1.970617351 days* | | | SPIV trips | 1 | SPIV Travel | 800 km |
| **Time per turbine: WOW** | 12 h | | | | | SPIV travel time | 26.99784017 hrs | SPIV Travel | 35.99712023 hrs |
| **Time in port: idle** | 24 h | | | | | SPIV OPS | 12000 hrs | SPIV DP | 24 hrs |
| | | | | | | SPIV DP | 2400 hrs | SPIV OPS | 200 hrs |
| **Time per foundation: OPS** | 60 hr | | | | | SPIV Idle | 24 hrs | Spiv Idle | 48 hrs |
| **Time per foundation: WOW** | 12 hr | | | | | | | | |
| **Time in port: Idle** | 24 hr | | | | | ROV vessel: | | OSV trips | 1 |
| | | | | | | OSV trips | 1 | OSV travel | 17.99856012 hr |
| **ROV per foundation** | 4 hr | | | | | OSV travel | 26.99784017 hr | OSV DP | 8 hr |
| **ROV waiing on weather** | 2 hr | | | | | OSV DP | 1200 hr | OSV idle | 24 hr |
| | | | | | | OSV idle | 24 hr | | |
| **Ship speed** | 12 kt | | | | | | | Jacket removal: | |
| **Tug speed** | 6 kt | | | | | | | | |
| | | | | | | | | Time to remove: | 101.8 hr |
| **Summary:** | | | | | | | | | |
| SPIV Travel | 521.9582433 hr | | | | | | | SPIV Travel | 800 km |
| SPIV DP | 4824 hr | | | | | | | SPIV Travel | 35.99712023 hr |
| SPIV ops | 18200 hr | | | | | | | SPIV DP | 24 |
| SPIV idle | 672 hr | | | | | | | SPIV OPS | 203.6 |
| | | | | | | | | Spiv Idle | 48 |
| AHTS Travel | 1205.903528 hr | | | | | | | AHTS Travel | 800 km |
| AHTS DP | 14803.6 hr | | | | | | | AHTS Travel | 71.99424046 hr |
| AHTS Idle | 696 hr | | | | | | | AHTS DP | 203.6 hr |
| OSV Travel | 44.99640029 hr | | | | | | | AHTS Idle | 48 hr |
| OSV DP | 1208 hr | | | | | | | | |
| OSV Idle | 48 hr | | | | | | | HLV DP | 203.6 hr |
| | hr | | | | | | | HLV Idle | 119.9942405 hr |
| CLV Travel | 34.19726422 hr | | | | | | | | |
| CLV DP | 10.79913607 hr | | | | | | | Substation and foundation barge | |
| CLV Idle | 24 hr | | | | | | | | |
| | | | | | | | | AHTS Travel | 1600 km |
| HLV DP | 403.6 hr | | | | | | | AHTS Travel | 143.9884809 hr |
| HLV Idle | 239.9884809 hr | | | | | | | AHTS DP | Negligble hr |
| | | | | | | | | AHTS Idle | 96 hr |

# F 12 MW windfarm

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 67 | | **Turbines:** | | | **Cables:** | | | **Foundations** | | | **Substation:** | | |
| **Turbine rating** | 12 | MW | Spiv Capacity | 3 | | CLV | | | Barges: | | | No. of substations | 2 | |
| **Farm output** | 804 | MW | SPIV trips | 23 | | CLV Trips | 1 | | Barge capacity | 8 | | | | |
| **Lifetime output** | 176076 | GWh | SPIV travel | 9267 | km | CLV op speed | 2 | kt | Barge trips | 9 | | AHTS Travel | 800 | km |
| **Foundations** | Monopile | | | | | CLV travel | 34.19726422 | hr | Barge Travel | 3667 | km | AHTS Travel | 71.99424046 | hr |
| **Distance to shore** | 100 | km | | | | CLV DP | 10.79913607 | hr | | | | AHTS DP | 200 | hr |
| **Distance to port** | 200 | km | SPIV travel time | 416.9816415 | Hrs | CLV idle | 24 | hr | | | | AHTS Idle | 48 | hr |
| **Export cable length** | 400 | km | SPIV ops time | 2010 | hrs | | | | AHTS/Barge Travel Time | 330.0035997 | hr | | | |
| **Cable removal** | 10 | % | SPIV idle time | 552 | hrs | | | | AHTS DP | 4824 | hr | HLV DP | 200 | hr |
| **No. of substations** | 2 | | SPIV DP | 804 | hrs | | | | AHTS idle | 216 | hr | HLV Idle | 119.9942405 | hr |
| | | | *Total* | *3782.981641* | *hrs* | | | | | | | | | |
| **Time per turbine: OPS** | 30 | h | *per turbine* | *2.352600523* | *days* | | | | SPIV trips | 1 | | SPIV Travel | 800 | km |
| **Time per turbine: WOW** | 12 | h | | | | | | | SPIV travel time | 21.01331893 | hrs | SPIV Travel | 35.99712023 | hrs |
| **Time in port: idle** | 24 | h | | | | | | | SPIV OPS | 4020 | hrs | SPIV DP | 24 | hrs |
| | | | | | | | | | SPIV DP | 804 | hrs | SPIV OPS | 200 | hrs |
| **Time per foundation: OPS** | 60 | hr | | | | | | | SPIV Idle | 24 | hrs | Spiv Idle | 48 | hrs |
| **Time per foundation: WOW** | 12 | hr | | | | | | | | | | | | |
| **Time in port: Idle** | 24 | hr | | | | | | | ROV vessel: | | | OSV trips | 1 | |
| | | | | | | | | | OSV trips | 1 | | OSV travel | 400 | hr |
| **ROV per foundation** | 4 | hr | | | | | | | OSV travel | 21.01331893 | hr | OSV DP | 8 | hr |
| **ROV waiing on weather** | 2 | hr | | | | | | | OSV DP | 402 | hr | OSV idle | 24 | hr |
| | | | | | | | | | OSV idle | 24 | hr | | | |
| **Ship speed** | 12 | kt | | | | | | | | | | Jacket removal: | | |
| **Tug speed** | 6 | kt | | | | | | | | | | | | |
| | | | | | | | | | | | | Time to remove: | 101.8 | hr |
| **Summary:** | | | | | | | | | | | | | | |
| SPIV Travel | 473.9920806 | hr | | | | | | | | | | SPIV Travel | 800 | km |
| SPIV DP | 1632 | hr | | | | | | | | | | SPIV Travel | 35.99712023 | hr |
| SPIV ops | 6230 | hr | | | | | | | | | | SPIV DP | 24 | |
| SPIV idle | 624 | hr | | | | | | | | | | SPIV OPS | 203.6 | |
| | | | | | | | | | | | | Spiv Idle | 48 | |
| AHTS Travel | 617.9805616 | hr | | | | | | | | | | | | |
| AHTS DP | 5227.6 | hr | | | | | | | | | | AHTS Travel | 800 | km |
| AHTS Idle | 312 | hr | | | | | | | | | | AHTS Travel | 71.99424046 | hr |
| | | | | | | | | | | | | AHTS DP | 203.6 | hr |
| OSV Travel | 39.01187905 | hr | | | | | | | | | | AHTS Idle | 48 | hr |
| OSV DP | 410 | hr | | | | | | | | | | | | |
| OSV Idle | 48 | hr | | | | | | | | | | HLV DP | 203.6 | hr |
| | | hr | | | | | | | | | | HLV Idle | 119.9942405 | hr |
| CLV Travel | 34.19726422 | hr | | | | | | | | | | | | |
| CLV DP | 10.79913607 | hr | | | | | | | | | | Substation and foundation barge | | |
| CLV Idle | 24 | hr | | | | | | | | | | | | |
| | | | | | | | | | | | | AHTS Travel | 1600 | km |
| HLV DP | 403.6 | hr | | | | | | | | | | AHTS Travel | 143.9884809 | hr |
| HLV Idle | 239.9884809 | hr | | | | | | | | | | AHTS DP | Negligble | hr |
| | | | | | | | | | | | | AHTS Idle | 96 | hr |

# G Floating windfarm

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No. of turbines** | 100 | | **Disconnect wires and mooring** | | | **Substation:** | | |
| **Turbine rating** | 8 | MW | | | | No. of substations | 2 | |
| **Farm output** | 800 | MW | **Mooring per turbine** | 2700 | m | | | |
| **Lifetime output** | 175200 | GWh | **total mooring** | 270000 | m | *AHTS Travel* | *800* | km |
| **Foundations** | Floating | | AHTS mooring capacity | 8143 | m, | AHTS Travel | 71.99424046 | hr |
| **Distance to shore** | 100 | km | **AHTS trips** | 34 | | AHTS DP | 200 | hr |
| **Distance to port** | 200 | km | **AHTS Travel** | 616.4506839 | hr | AHTS Idle | 48 | hr |
| **Export cable length** | 300 | km | **AHTS DP** | 1000 | hr | | | |
| **Cable removal** | 400 | km | **AHTS Idle** | 816 | hr | HLV DP | 200 | hr |
| **No. of substations** | 10 | % | | | | HLV Idle | 119.9942405 | hr |
| **No. of substations** | 2 | | | | | | | |
| **Time to free suction Caisssons** | 4 | hrs | | | | SPIV Travel | 800 | km |
| **Idle time Port** | 12 | hrs | | | | SPIV Travel | 35.99712023 | hrs |
| | | | | | | SPIV DP | 24 | hrs |
| **Cut and recover cables** | 10 | hr | | | | SPIV OPS | 200 | hrs |
| | | | | | | Spiv Idle | 48 | hrs |
| **Vessels** | | | | | | | | |
| **Tow WTGs:** | | | | | | OSV trips | 1 | |
| | | | | | | OSV travel | 17.99856012 | hr |
| **AHTS Travel** | 40000 | km | | | | OSV DP | 8 | hr |
| **AHTS Travel** | 2399.808015 | hrs | | | | OSV idle | 24 | hr |
| **AHTS DP** | 400 | hrs | | | | | | |
| **AHTS idle** | 1200 | hrs | | | | Jacket removal: | | |
| | | | | | | | | |
| **Summary** | | | | | | Time to remove: | 101.8 | hr |
| | | | | | | | | |
| AHTS Travel | 3232.241421 | hr | | | | SPIV Travel | 800 | km |
| AHTS DP | 1600 | hr | | | | SPIV Travel | 35.99712023 | hr |
| AHTS Idle | 2208 | hr | | | | SPIV DP | 24 | |
| | | | | | | SPIV OPS | 203.6 | |
| SPIV Travel | 71.99424046 | hr | | | | Spiv Idle | 48 | |
| Spiv DP | 48 | hr | | | | | | |
| Spiv Ops | 403.6 | hr | | | | AHTS Travel | 800 | km |
| Spiv Idle | 96 | hr | | | | AHTS Travel | 71.99424046 | hr |
| | | | | | | AHTS DP | 203.6 | hr |
| HLP DP | 403.6 | hr | | | | AHTS Idle | 48 | hr |
| HLP Idle | 239.9884809 | hr | | | | | | |
| | | | | | | HLP DP | 203.6 | hr |
| OSV travel | 17.99856012 | hr | | | | HLP Idle | 119.9942405 | hr |
| OSV DP | 8 | hr | | | | | | |
| OSV idle | 24 | hr | | | | Substation and foundation barge | | |
| | | | | | | | | |
| | | | | | | AHTS Travel | 1600 | km |
| | | | | | | AHTS Travel | 143.9884809 | hr |
| | | | | | | AHTS DP | Negligble | hr |
| | | | | | | AHTS Idle | 96 | hr |

# H Vessel energy demand

| Vessel Name | Vessel type | MCR | Fuel consumption: Tonnes/day | Specific Fuel Consumption | Energy Demand: Travel [MW] | Energy Demand: DP [MW] | Energy Demand: Ops [MW] | Energy Demand: Idle [MW] |
|---|---|---|---|---|---|---|---|---|
| **SPIV:** | | | | | | | | |
| MPI Resolution | SPIV | 9020 | 18.50 | 180g/kWh | 4.3 | 2.1 | 1.6 | 1.1 |
| Bold Tern | SPIV | 17100 | Extrapolated,based on data from MPI Resolution | | 8.1 | 4.1 | 3.0 | 2.0 |
| Brave tern | SPIV | 18000 | Extrapolated,based on data from MPI Resolution | | 8.5 | 4.3 | 3.2 | 2.1 |
| MPI Adventure | SPIV | 13920 | Extrapolated,based on data from MPI Resolution | | 6.6 | 3.3 | 2.5 | 1.7 |
| Innovation | SPIV | 27000 | Extrapolated,based on data from MPI Resolution | | 12.8 | 6.4 | 4.8 | 3.2 |
| Sea Installer | SPIV | 17820 | Extrapolated,based on data from MPI Resolution | | 8.5 | 4.3 | 3.2 | 2.1 |
| Sea Challanger | SPIV | 17820 | Extrapolated,based on data from MPI Resolution | | 8.5 | 4.3 | 3.2 | 2.1 |
| *Average* | | | | | *8.2* | *4.1* | *3.1* | *2.0* |
| **OSV:** | | | | | | | | |
| NOR GOLIATH | OSV | 20 000 | 40.00 | 180g/kWh | 9.3 | 4.6 | 4.6 | 2.3 |
| DELMA 2000 | OSV | 20 200 | 40.00 | 180g/kWh | 9.3 | 4.6 | 4.6 | 2.3 |
| NORMAND SAMSON | OSV | 24 000 | 35.00 | 180g/kWh | 8.1 | 4.1 | 4.1 | 2.0 |
| ONYX | OSV | 15 660 | 34.00 | 180g/kWh | 7.9 | 3.9 | 3.9 | 2.0 |
| MAERSK NOMAD | OSV | 7 680 | 34.00 | 180g/kWh | 7.9 | 3.9 | 3.9 | 2.0 |
| ISLAND PERFORMER | OSV | 15 660 | 34.00 | 180g/kWh | 7.9 | 3.9 | 3.9 | 2.0 |
| ARIADNE | OSV | 15 300 | 34.00 | 180g/kWh | 7.9 | 3.9 | 3.9 | 2.0 |
| NORMAND JARL | OSV | 13 536 | 31.50 | 180g/kWh | 7.3 | 3.6 | 3.6 | 1.8 |
| DEEP CYGNUS | OSV | 12 480 | 31.00 | 180g/kWh | 7.2 | 3.6 | 3.6 | 1.8 |
| NORMAND MERMAID | OSV | 10 440 | 30.00 | 180g/kWh | 6.9 | 3.5 | 3.5 | 1.7 |
| EDDA FAUNA | OSV | 10 950 | 30.00 | 180g/kWh | 6.9 | 3.5 | 3.5 | 1.7 |
| Normand Sapphire | AHTS | 16 000 | 20.00 | 180g/kWh | 4.6 | 2.3 | 2.3 | 1.2 |
| Dina Star | OSV | 9 400 | 21.00 | 180g/kWh | 4.9 | 2.4 | 2.4 | 1.2 |
| Edda Flora | RSV | 9 120 | 29.00 | 180g/kWh | 6.7 | 3.4 | 3.4 | 1.7 |
| Normand Ocean | OSV | 9 225 | 31.50 | 180g/kWh | 7.3 | 3.6 | 3.6 | 1.8 |
| *Average* | | | | | *7.3* | *3.7* | *3.7* | *1.8* |
| **AHTS:** | | | | | | | | |
| FAR SABRE | AHTS | 10 812 | 21.00 | 180g/kWh | 4.9 | 2.4 | 2.4 | 1.2 |
| SEA TIGER | AHTS | 11 034 | 35.00 | 180g/kWh | 8.1 | 4.1 | 4.1 | 2.0 |
| BEAR | AHTS | 11 040 | 32.00 | 180g/kWh | 7.4 | 3.7 | 3.7 | 1.9 |
| GERARD JORDAN | AHTS | 10 296 | 29.00 | 180g/kWh | 6.7 | 3.4 | 3.4 | 1.7 |
| ATLANTIC BRIGAND | AHTS | 9 000 | 34.00 | 180g/kWh | 7.9 | 3.9 | 3.9 | 2.0 |
| Normand Sapphire | AHTS | | 20.00 | 180g/kWh | 4.6 | 2.3 | 2.3 | 1.2 |
| Dina Star | OSV | | 21.00 | 180g/kWh | 4.9 | 2.4 | 2.4 | 1.2 |
| *Average* | | | | | *6.3* | *3.2* | *3.2* | *1.6* |
| **Small CLV:** | | | | | | | | |
| ILE D`OUESSANT | CRV | 6000 | 25.20 | 180g/kWh | 5.8 | 2.9 | 2.9 | 1.5 |
| ILE D AIX | CRV | 9990 | 25.00 | 180g/kWh | 5.8 | 2.9 | 2.9 | 1.4 |
| CS NUSANTARA EXPLORER | CRV | 7920 | 20.00 | 180g/kWh | 4.6 | 2.3 | 2.3 | 1.2 |
| GIULIO VERNE | CLV | 8090 | 15.00 | 180g/kWh | 3.5 | 1.7 | 1.7 | 0.9 |
| *Average* | | | | | *4.9* | *2.5* | *2.5* | *1.2* |
| **Large CLV:** | | | | | | | | |
| SEVEN SUN | Pipe Layer | 23040 | 41.00 | 180g/kWh | 9.5 | 4.7 | 4.7 | 2.4 |
| SEVEN RIO | Pipe Layer | 23040 | 41.00 | 180g/kWh | 9.5 | 4.7 | 4.7 | 2.4 |
| SEVEN CRUZEIRO | Pipe Layer | 23700 | 41.00 | 180g/kWh | 9.5 | 4.7 | 4.7 | 2.4 |
| SAPURA ONIX | Pipe Layer | 15360 | 41.00 | 180g/kWh | 9.5 | 4.7 | 4.7 | 2.4 |
| SAPURA JADE | Pipe Layer | 23040 | 41.00 | 180g/kWh | 9.5 | 4.7 | 4.7 | 2.4 |
| NOR GOLIATH | OSV | 20000 | 40.00 | 180g/kWh | 9.3 | 4.6 | 4.6 | 2.3 |
| DELMA 2000 | OSV | 20200 | 40.00 | 180g/kWh | 9.3 | 4.6 | 4.6 | 2.3 |
| SEVEN WAVES | Pipe Layer | 22040 | 38.80 | 180g/kWh | 9.0 | 4.5 | 4.5 | 2.2 |
| OCEAN CONSTRUCTOR | Pipe Layer | 13240 | 35.00 | 180g/kWh | 8.1 | 4.1 | 4.1 | 2.0 |
| *Average* | | | | | *9.2* | *4.6* | *4.6* | *2.3* |

# I Results from SIMApro/ CML Baseline 3.01

**Basecase**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Sm | DP CLV Sma | Idle CLV Small | DP HLP 1hr | Idle HLP 1h | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.17926601 | 0.51368267 | 1.43179 | 0.05848862 | 0.38985314 | 1.4594567 | 0.05527954 | 0.0132352 | 0.09966918 | 0.0039841 | 0.009224969 | 0.0014566 | 0.001618545 | 0.1381864 | 0.0410842 | 4.396275874 |
| Abiotic depletion (fossil | MJ | 16625335 | 47639517 | 1.33E+08 | 5424301.5 | 36155426 | 1.35E+08 | 5126688 | 1227449.1 | 9243433.9 | 369491.03 | 855534.11 | 135084.4 | 150105.73 | 12815565 | 3810193.7 | 407715644.5 |
| **Global warming (GWP1** | **kg CO2 e** | **1138523.1** | **3262411.9** | **9093335** | **371462.74** | **2475967.3** | **9269047.3** | **351081.8** | **84057.204** | **633001.55** | **25303.193** | **58588.012** | **9250.7433** | **10279.422** | **877625.44** | **260926.68** | **27920861.38** |
| Ozone layer depletion ( | kg CFC-11 | 0.20514912 | 0.58785011 | 1.6385172 | 0.06693343 | 0.44614161 | 1.6701786 | 0.06326101 | 0.0151462 | 0.1140598 | 0.0045594 | 0.010556904 | 0.0016669 | 0.001852237 | 0.1581383 | 0.0470161 | 5.031026771 |
| Human toxicity | kg 1,4-DB | 149989.07 | 429790.26 | 1197956.3 | 48936.515 | 326184.03 | 1221104.6 | 46251.53 | 11073.699 | 83391.648 | 3333.4436 | 7718.387 | 1218.6933 | 1354.2115 | 115618.41 | 34374.49 | 3678295.287 |
| Fresh water aquatic eco | kg 1,4-DB | 118457.8 | 339438.12 | 946117.37 | 38648.895 | 257612.38 | 964399.38 | 36528.358 | 8745.744 | 65860.739 | 2632.6744 | 6095.7983 | 962.49494 | 1069.524 | 91312.667 | 27148.154 | 2905030.099 |
| Marine aquatic ecotoxic | kg 1,4-DB | 3.25E+08 | 9.31E+08 | 2.60E+09 | 1.06E+08 | 7.07E+08 | 2.65E+09 | 1.00E+08 | 2.40E+07 | 1.81E+08 | 7221065.9 | 16719941 | 2639992 | 2933558 | 2.50E+08 | 74463674 | 7968100301 |
| Terrestrial ecotoxicity | kg 1,4-DB | 609.30371 | 1745.9459 | 4866.4827 | 198.79582 | 1325.0642 | 4960.5187 | 187.88855 | 44.984918 | 338.76362 | 13.541517 | 31.354563 | 4.950723 | 5.5012414 | 469.67906 | 139.6402 | 14942.41542 |
| Photochemical oxidatio | kg C2H4 e | 396.64387 | 1136.574 | 3167.9777 | 129.41189 | 862.58883 | 3229.1931 | 122.31149 | 29.284233 | 220.52798 | 8.8152422 | 20.41116 | 3.2228163 | 3.5811922 | 305.75117 | 90.90283 | 9727.197504 |
| Acidification | kg SO2 ec | 11883.445 | 34051.742 | 94912.571 | 3877.1785 | 25843.15 | 96746.584 | 3664.4505 | 877.35525 | 6607.0153 | 264.10454 | 611.51809 | 96.555535 | 107.29247 | 9160.301 | 2723.4476 | 291426.7108 |
| Eutrophication | kg PO4--- | 3119.1329 | 8937.8043 | 24912.381 | 1017.6708 | 6783.2366 | 25393.768 | 961.83456 | 230.28571 | 1734.1906 | 69.321409 | 160.50953 | 25.343622 | 28.161823 | 2404.3698 | 714.84278 | 76492.85343 |

**Basecase, return on SPIV**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Sm | DP CLV Sma | Idle CLV Small | DP HLP 1hr | Idle HLP 1h | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.43100138 | 0.51368267 | 1.43179 | 0.14240708 | 0.11040087 | 0.07746814 | 0.01842652 | 0.0132352 | 0.09966918 | 0.0039841 | 0.009224969 | 0.0014566 | 0.001618545 | 0.1381864 | 0.0410842 | 3.033635842 |
| Abiotic depletion (fossil | MJ | 39971560 | 47639517 | 1.33E+08 | 13206995 | 10238702 | 7.18E+06 | 1708896 | 1227449.1 | 9243433.9 | 369491.03 | 855534.11 | 135084.4 | 150105.73 | 12815565 | 3810193.7 | 281342850.6 |
| **Global warming (GWP1** | **kg CO2 e** | **2737300.8** | **3262411.9** | **9093335** | **904431.01** | **701158.74** | **492002.14** | **117027.27** | **84057.204** | **633001.55** | **25303.193** | **58588.012** | **9250.7433** | **10279.422** | **877625.44** | **260926.68** | **19266699.1** |
| Ozone layer depletion ( | kg CFC-11 | 0.49323098 | 0.58785011 | 1.6385172 | 0.16296835 | 0.12634096 | 0.08865328 | 0.021087 | 0.0151462 | 0.1140598 | 0.0045594 | 0.010556904 | 0.0016669 | 0.001852237 | 0.1581383 | 0.0470161 | 3.471643574 |
| Human toxicity | kg 1,4-DB | 360612.12 | 429790.26 | 1197956.3 | 119149.78 | 92370.679 | 64816.381 | 15417.177 | 11073.699 | 83391.648 | 3333.4436 | 7718.387 | 1218.6933 | 1354.2115 | 115618.41 | 34374.49 | 2538195.679 |
| Fresh water aquatic eco | kg 1,4-DB | 284802.86 | 339438.12 | 946117.37 | 94101.657 | 72952.164 | 51190.435 | 12176.119 | 8745.744 | 65860.739 | 2632.6744 | 6095.7983 | 962.49494 | 1069.524 | 91312.667 | 27148.154 | 2004606.521 |
| Marine aquatic ecotoxic | kg 1,4-DB | 7.81E+08 | 9.31E+08 | 2.60E+09 | 2.58E+08 | 2.00E+08 | 1.40E+08 | 33397430 | 23988380 | 1.81E+08 | 7221065.9 | 16719941 | 2639992 | 2933558 | 2.50E+08 | 74463674 | 5498361591 |
| Terrestrial ecotoxicity | kg 1,4-DB | 1464.9221 | 1745.9459 | 4866.4827 | 484.0246 | 375.23933 | 263.30493 | 62.629517 | 44.984918 | 338.76362 | 13.541517 | 31.354563 | 4.950723 | 5.5012414 | 469.67906 | 139.6402 | 10310.96492 |
| Photochemical oxidatio | kg C2H4 e | 953.63339 | 1136.574 | 3167.9777 | 315.08981 | 244.27289 | 171.40596 | 40.770495 | 29.284233 | 220.52798 | 8.8152422 | 20.41116 | 3.2228163 | 3.5811922 | 305.75117 | 90.90283 | 6712.220869 |
| Acidification | kg SO2 ec | 28570.844 | 34051.742 | 94912.571 | 9440.0868 | 7318.4127 | 5135.3203 | 1221.4835 | 877.35525 | 6607.0153 | 264.10454 | 611.51809 | 96.555535 | 107.29247 | 9160.301 | 2723.4476 | 201098.0501 |
| Eutrophication | kg PO4--- | 7499.1939 | 8937.8043 | 24912.381 | 2477.8071 | 1920.9161 | 1347.9043 | 320.61152 | 230.28571 | 1734.1906 | 69.321409 | 160.50953 | 25.343622 | 28.161823 | 2404.3698 | 714.84278 | 52783.64349 |

**GBF - New Vessel**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Sm | DP CLV Sma | Idle CLV Small | DP HLP 1hr | Idle HLP 1h | Travel Large HL | DP Large HLV | Idle Large HL | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.16973059 | 0.25938432 | 4.99E-01 | 0.05594564 | 0.11040087 | 7.75E-02 | 0.01842652 | 0.0132416 | 0.09966918 | 0.0039841 | 0.009224969 | 0.0014566 | 0.001618545 | 0.1381864 | 0.0410842 | 0.35735082 | 3.7967335 | 0.07096698 | 5.723447091 |
| Abiotic depletion (fossil | MJ | 15741008 | 24055598 | 4.62E+07 | 5188462.3 | 10238702 | 7184483.6 | 1708896 | 1228039 | 9243433.9 | 369491.03 | 855534.11 | 135084.4 | 150105.73 | 12815565 | 3810193.7 | 33141123 | 3.52E+08 | 6581558.9 | 530799016.7 |
| **Global warming (GWP1** | **kg CO2 e** | **1077963.3** | **1647356.5** | **3166457.4** | **355312.18** | **701158.74** | **492002.14** | **117027.27** | **84097.596** | **633001.55** | **25303.193** | **58588.012** | **9250.7433** | **10279.422** | **877625.44** | **260926.68** | **2269544.2** | **24113152** | **450713.13** | 36349759.5 |
| Ozone layer depletion ( | kg CFC-11 | 0.19423693 | 0.29683521 | 0.5705602 | 0.06402328 | 0.12634096 | 0.08865328 | 0.021087 | 0.0151534 | 0.1140598 | 0.0045594 | 0.010556904 | 0.0016669 | 0.001852237 | 0.1581383 | 0.0470161 | 0.40894648 | 4.3449202 | 0.08121346 | 6.549819965 |
| Human toxicity | kg 1,4-DB | 142010.93 | 217022.81 | 417149.22 | 46808.841 | 92370.679 | 64816.381 | 15417.177 | 11079.021 | 83391.648 | 3333.4436 | 7718.387 | 1218.6933 | 1354.2115 | 115618.41 | 34374.49 | 298989.85 | 3176667.6 | 59376.965 | 4788718.757 |
| Fresh water aquatic eco | kg 1,4-DB | 1.12E+05 | 1.71E+05 | 3.29E+05 | 3.70E+04 | 7.30E+04 | 5.12E+04 | 1.22E+04 | 8.75E+03 | 6.59E+04 | 2632.6744 | 6095.7983 | 962.49494 | 1069.524 | 9.13E+04 | 27148.154 | 236135.06 | 2508856.5 | 46894.513 | 3782016.117 |
| Marine aquatic ecotoxic | kg 1,4-DB | 3.08E+08 | 4.70E+08 | 9.04E+08 | 1.01E+08 | 2.00E+08 | 1.40E+08 | 33397430 | 23999907 | 1.81E+08 | 7221065.9 | 16719941 | 2639992 | 2933558 | 2.50E+08 | 74463674 | 6.48E+08 | 6.88E+09 | 1.29E+08 | 10373552828 |
| Terrestrial ecotoxicity | kg 1,4-DB | 576.89394 | 881.61624 | 1694.5939 | 190.15252 | 375.23933 | 263.30493 | 62.629517 | 45.006535 | 338.76362 | 13.541517 | 31.354563 | 4.950723 | 5.5012414 | 469.67906 | 139.6402 | 1214.5927 | 12904.643 | 241.20827 | 19453.31181 |
| Photochemical oxidatio | kg C2H4 e | 375.5458 | 573.91359 | 1103.1449 | 123.78528 | 244.27289 | 171.40596 | 40.770495 | 29.298305 | 220.52798 | 8.8152422 | 20.41116 | 3.2228163 | 3.5811922 | 305.75117 | 90.90283 | 790.67421 | 8400.6504 | 157.0215 | 12663.69572 |
| Acidification | kg SO2 ec | 11251.347 | 17194.444 | 33050.208 | 3708.6055 | 7318.4127 | 5135.3203 | 1221.4835 | 877.77685 | 6607.0153 | 264.10454 | 611.51809 | 96.555535 | 107.29247 | 9160.301 | 2723.4476 | 23688.589 | 251683.38 | 4704.3622 | 379404.1636 |
| Eutrophication | kg PO4--- | 2953.2216 | 4513.1487 | 8674.9245 | 973.42423 | 1920.9161 | 1347.9043 | 320.61152 | 230.39637 | 1734.1906 | 69.321409 | 160.50953 | 25.343622 | 28.161823 | 2404.3698 | 714.84278 | 6217.7135 | 66061.137 | 1234.7876 | 99584.92498 |

**GBF**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Sm | DP CLV Sma | Idle CLV Small | DP HLP 1hr | Idle HLP 1h | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.16973059 | 0.25938432 | 0.4985742 | 0.05594564 | 0.82110646 | 5.0065608 | 0.13589555 | 0.0132416 | 0.09966918 | 0.0039841 | 0.009224969 | 0.0014566 | 0.001618545 | 4.5343699 | 0.0451928 | 11.65595518 |
| Abiotic depletion (fossil | MJ | 15741008 | 24055598 | 46238338 | 5188462.3 | 76150351 | 4.64E+08 | 12603108 | 1228039 | 9243433.9 | 369491.03 | 855534.11 | 135084.4 | 150105.73 | 4.21E+08 | 4191231.3 | 1080986605 |
| **Global warming (GWP1** | **kg $CO_2$ e** | **1077963.3** | **1647356.5** | **3166457.4** | **355312.18** | **5214868.3** | **31796796** | **863076.1** | **84097.596** | **633001.55** | **25303.193** | **58588.012** | **9250.7433** | **10279.422** | **28797900** | **287020.59** | **74027270.89** |
| Ozone layer depletion ( | kg CFC-11 | 0.19423693 | 0.29683521 | 0.5705602 | 0.06402328 | 0.93966092 | 5.7294269 | 0.15551666 | 0.0151534 | 0.1140598 | 0.0045594 | 0.010556904 | 0.0016669 | 0.001852237 | 5.1890594 | 0.0517179 | 13.33888601 |
| Human toxicity | kg 1,4-DB | 142010.93 | 217022.81 | 417149.22 | 46808.841 | 687006.95 | 4188911.2 | 113701.68 | 11079.021 | 83391.648 | 3333.4436 | 7718.387 | 1218.6933 | 1354.2115 | 3793836.5 | 37812.104 | 9752355.639 |
| Fresh water aquatic eco | kg 1,4-DB | 112156.85 | 171399.45 | 329454.52 | 36968.508 | 542581.73 | 3308302.3 | 89798.879 | 8749.9467 | 65860.739 | 2632.6744 | 6095.7983 | 962.49494 | 1069.524 | 2996281.7 | 29863.1 | 7702178.214 |
| Marine aquatic ecotoxic | kg 1,4-DB | 3.08E+08 | 4.70E+08 | 9.04E+08 | 1.01E+08 | 1.49E+09 | 9.07E+09 | 2.46E+08 | 23999907 | 1.81E+08 | 7221065.9 | 16719941 | 2639992 | 2933558 | 8.22E+09 | 81910398 | 21126021612 |
| Terrestrial ecotoxicity | kg 1,4-DB | 576.89394 | 881.61624 | 1694.5939 | 190.15252 | 2790.8426 | 17016.701 | 461.89269 | 45.006535 | 338.76362 | 13.541517 | 31.354563 | 4.950723 | 5.5012414 | 15411.781 | 153.60489 | 39617.19698 |
| Photochemical oxidatio | kg $C_2H_4$ e | 375.5458 | 573.91359 | 1103.1449 | 123.78528 | 1816.7797 | 11077.513 | 300.6824 | 29.298305 | 220.52798 | 8.8152422 | 20.41116 | 3.2228163 | 3.5811922 | 1.00E+04 | 99.993548 | 25789.95891 |
| Acidification | kg $SO_2$ e | 11251.347 | 17194.444 | 33050.208 | 3708.6055 | 54430.696 | 3.32E+05 | 9008.4409 | 877.77685 | 6.61E+03 | 264.10454 | 611.51809 | 96.555535 | 107.29247 | 3.01E+05 | 2995.8054 | 772666.8596 |
| Eutrophication | kg $PO_4$--- | 2953.2216 | 4513.1487 | 8674.9245 | 973.42423 | 14286.814 | 87111.485 | 2364.5099 | 230.39637 | 1734.1906 | 69.321409 | 160.50953 | 25.343622 | 28.161823 | 78895.617 | 786.33048 | 202807.3988 |

**Jacket**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Sm | DP CLV Sma | Idle CLV Small | DP HLP 1hr | Idle HLP 1h | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.16973059 | 0.25938432 | 0.4985742 | 0.05594564 | 0.60030473 | 5.0065608 | 0.09904252 | 0.0132416 | 0.09966918 | 0.0039841 | 0.009224969 | 0.0014566 | 0.001618545 | 4.5344042 | 0.0451928 | 11.39833472 |
| Abiotic depletion (fossil | MJ | 15741008 | 24055598 | 46238338 | 5188462.3 | 55672946 | 4.64E+08 | 9185316 | 1228039 | 9243433.9 | 369491.03 | 855534.11 | 135084.4 | 150105.73 | 4.21E+08 | 4191231.3 | 1057094578 |
| **Global warming (GWP1** | **kg $CO_2$ e** | **1077963.3** | **1647356.5** | **3166457.4** | **355312.18** | **3812550.8** | **31796796** | **629021.57** | **84097.596** | **633001.55** | **25303.193** | **58588.012** | **9250.7433** | **10279.422** | **28798118** | **287020.59** | **72391116.86** |
| Ozone layer depletion ( | kg CFC-11 | 0.19423693 | 0.29683521 | 0.5705602 | 0.06402328 | 0.686979 | 5.7294269 | 0.11334265 | 0.0151534 | 0.1140598 | 0.0045594 | 0.010556904 | 0.0016669 | 0.001852237 | 5.1890986 | 0.0517179 | 13.04406928 |
| Human toxicity | kg 1,4-DB | 142010.93 | 217022.81 | 417149.22 | 46808.841 | 502265.59 | 4188911.2 | 82867.325 | 11079.021 | 83391.648 | 3333.4436 | 7718.387 | 1218.6933 | 1354.2115 | 3793865.1 | 37812.104 | 9536808.524 |
| Fresh water aquatic eco | kg 1,4-DB | 112156.85 | 171399.45 | 329454.52 | 36968.508 | 396677.41 | 3308302.3 | 65446.641 | 8749.9467 | 65860.739 | 2632.6744 | 6095.7983 | 962.49494 | 1069.524 | 2996304.4 | 29863.1 | 7531944.356 |
| Marine aquatic ecotoxic | kg 1,4-DB | 3.08E+08 | 4.70E+08 | 9.04E+08 | 1.01E+08 | 1.09E+09 | 9.07E+09 | 1.80E+08 | 23999907 | 1.81E+08 | 7221065.9 | 16719941 | 2639992 | 2933558 | 8.22E+09 | 81910398 | 20659093262 |
| Terrestrial ecotoxicity | kg 1,4-DB | 576.89394 | 881.61624 | 1694.5939 | 190.15252 | 2040.3639 | 17016.701 | 336.63365 | 45.006535 | 338.76362 | 13.541517 | 31.354563 | 4.950723 | 5.5012414 | 15411.897 | 153.60489 | 38741.57524 |
| Photochemical oxidatio | kg $C_2H_4$ e | 375.5458 | 573.91359 | 1103.1449 | 123.78528 | 1328.2339 | 11077.513 | 219.14141 | 29.298305 | 220.52798 | 8.8152422 | 20.41116 | 3.2228163 | 3.5811922 | 1.00E+04 | 99.993548 | 25219.94812 |
| Acidification | kg $SO_2$ e | 11251.347 | 17194.444 | 33050.208 | 3708.6055 | 39793.87 | 3.32E+05 | 6565.4739 | 877.77685 | 6.61E+03 | 264.10454 | 611.51809 | 96.555535 | 107.29247 | 3.01E+05 | 2995.8054 | 755589.3366 |
| Eutrophication | kg $PO_4$--- | 2953.2216 | 4513.1487 | 8674.9245 | 973.42423 | 10444.982 | 87111.485 | 1723.2869 | 230.39637 | 1734.1906 | 69.321409 | 160.50953 | 25.343622 | 28.161823 | 78896.212 | 786.33048 | 198324.9388 |

**Jacket - New vessel**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Sm | DP CLV Sma | Idle CLV Small | DP HLP 1hr | Idle HLP 1h | Travel Large HL | DP Large HLV | Idle Large HL | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.16973059 | 0.25938432 | 4.99E-01 | 0.02034387 | 0.11040087 | 7.75E-02 | 0.01842652 | 0.0132416 | 0.09966918 | 0.0039841 | 0.009224969 | 0.0014566 | 0.001618545 | 0.1381864 | 0.0410842 | 0.23382215 | 3.7967335 | 0.04612854 | 5.539478208 |
| Abiotic depletion (fossil | MJ | 15741008 | 24055598 | 4.62E+07 | 1886713.6 | 10238702 | 7184483.6 | 1708896 | 1228039 | 9243433.9 | 369491.03 | 855534.11 | 135084.4 | 150105.73 | 12815565 | 3810193.7 | 21684933 | 3.52E+08 | 4278013.3 | 513737532.4 |
| **Global warming (GWP1** | **kg $CO_2$ e** | **1077963.3** | **1647356.5** | **3166457.4** | **129204.43** | **701158.74** | **492002.14** | **117027.27** | **84097.596** | **633001.55** | **25303.193** | **58588.012** | **9250.7433** | **10279.422** | **877625.44** | **260926.68** | **1485010.5** | **24113152** | **292963.53** | **35181368.45** |
| Ozone layer depletion ( | kg CFC-11 | 0.19423693 | 0.29683521 | 0.5705602 | 0.02328119 | 0.12634096 | 0.08865328 | 0.021087 | 0.0151534 | 0.1140598 | 0.0045594 | 0.010556904 | 0.0016669 | 0.001852237 | 0.1581383 | 0.0470161 | 0.26758227 | 4.3449202 | 0.05278875 | 6.339288956 |
| Human toxicity | kg 1,4-DB | 142010.93 | 217022.81 | 417149.22 | 17021.397 | 92370.679 | 64816.381 | 15417.177 | 11079.021 | 83391.648 | 3333.4436 | 7718.387 | 1218.6933 | 1354.2115 | 115618.41 | 34374.49 | 195635.34 | 3176667.6 | 38595.027 | 4634794.865 |
| Fresh water aquatic eco | kg 1,4-DB | 1.12E+05 | 1.71E+05 | 3.29E+05 | 1.34E+04 | 7.30E+04 | 5.12E+04 | 1.22E+04 | 8.75E+03 | 6.59E+04 | 2632.6744 | 6095.7983 | 962.49494 | 1069.524 | 9.13E+04 | 27148.154 | 154508.13 | 2508856.5 | 30481.434 | 3660450.694 |
| Marine aquatic ecotoxic | kg 1,4-DB | 3.08E+08 | 4.70E+08 | 9.04E+08 | 3.69E+07 | 2.00E+08 | 1.40E+08 | 33397430 | 23999907 | 1.81E+08 | 7221065.9 | 16719941 | 2639992 | 2933558 | 2.50E+08 | 74463674 | 4.24E+08 | 6.88E+09 | 8.36E+07 | 10040115490 |
| Terrestrial ecotoxicity | kg 1,4-DB | 576.89394 | 881.61624 | 1694.5939 | 69.146372 | 375.23933 | 263.30493 | 62.629517 | 45.006535 | 338.76362 | 13.541517 | 31.354563 | 4.950723 | 5.5012414 | 469.67906 | 139.6402 | 794.73348 | 12904.643 | 156.78538 | 18828.02355 |
| Photochemical oxidatio | kg $C_2H_4$ e | 375.5458 | 573.91359 | 1103.1449 | 45.012831 | 244.27289 | 171.40596 | 40.770495 | 29.298305 | 220.52798 | 8.8152422 | 20.41116 | 3.2228163 | 3.5811922 | 305.75117 | 90.90283 | 517.35475 | 8400.6504 | 102.06398 | 12256.64629 |
| Acidification | kg $SO_2$ e | 11251.347 | 17194.444 | 33050.208 | 1348.5838 | 7318.4127 | 5135.3203 | 1221.4835 | 877.77685 | 6607.0153 | 264.10454 | 611.51809 | 96.555535 | 107.29247 | 9160.301 | 2723.4476 | 15499.942 | 251683.38 | 3057.8354 | 367208.9681 |
| Eutrophication | kg $PO_4$--- | 2953.2216 | 4513.1487 | 8674.9245 | 353.97245 | 1920.9161 | 1347.9043 | 320.61152 | 230.39637 | 1734.1906 | 69.321409 | 160.50953 | 25.343622 | 28.161823 | 2404.3698 | 714.84278 | 4068.3806 | 66061.137 | 802.61194 | 96383.96464 |

**4 MW turbines**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Sm | DP CLV Smal | Idle CLV Small | DP HLP 1hr | Idle HLP 1h | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.22122185 | 1.0222794 | 2.8324541 | 0.07120354 | 0.66930503 | 2.8414453 | 0.10134583 | 0.0147058 | 0.19802693 | 0.0039841 | 0.009224969 | 0.0014566 | 0.001618545 | 0.1381864 | 0.0410842 | 8.167542565 |
| Abiotic depletion (fossil | MJ | 20516367 | 94807357 | 2.63E+08 | 6603497.5 | 62072113 | 2.64E+08 | 9398928 | 1363832.4 | 18365244 | 369491.03 | 855534.11 | 135084.4 | 150105.73 | 12815565 | 3810193.7 | 757467222.9 |
| **Global warming (GWP1** | **kg CO2 e** | **1404985.7** | **6492522.6** | **17988989** | **452215.5** | **4250773.5** | **18046092** | **643649.98** | **93396.893** | **1257674.1** | **25303.193** | **58588.012** | **9250.7433** | **10279.422** | **877625.44** | **260926.68** | **51872272.76** |
| Ozone layer depletion ( | kg CFC-11 | 0.2531627 | 1.1698799 | 3.2414145 | 0.08148417 | 0.76594182 | 3.2517039 | 0.11597852 | 0.0168291 | 0.22661881 | 0.0045594 | 0.010556904 | 0.0016669 | 0.001852237 | 0.1581383 | 0.0470161 | 9.34680312 |
| Human toxicity | kg 1,4-DB | 185092.86 | 855325.18 | 2369870.1 | 59574.888 | 559997.06 | 2377392.9 | 84794.472 | 12304.11 | 165686.04 | 3333.4436 | 7718.387 | 1218.6933 | 1354.2115 | 115618.41 | 34374.49 | 6833655.245 |
| Fresh water aquatic eco | kg 1,4-DB | 146181.94 | 675515.46 | 1871667 | 47050.828 | 442272.35 | 1877608.3 | 66968.656 | 9717.4934 | 130854.89 | 2632.6744 | 6095.7983 | 962.49494 | 1069.524 | 91312.667 | 27148.154 | 5397058.23 |
| Marine aquatic ecotoxic | kg 1,4-DB | 4.01E+08 | 1.85E+09 | 5.13E+09 | 1.29E+08 | 1.21E+09 | 5.15E+09 | 1.84E+08 | 2.67E+07 | 3.59E+08 | 7221065.9 | 16719941 | 2639992 | 2933558 | 2.50E+08 | 74463674 | 14803392516 |
| Terrestrial ecotoxicity | kg 1,4-DB | 751.90658 | 3474.6052 | 9627.1724 | 242.0123 | 2274.8877 | 9657.7325 | 344.46234 | 49.983242 | 673.06983 | 13.541517 | 31.354563 | 4.950723 | 5.5012414 | 469.67906 | 139.6402 | 27760.4994 |
| Photochemical oxidatio | kg C2H4 e | 489.47533 | 2261.8947 | 6267.0863 | 157.54491 | 1480.9039 | 6286.9803 | 224.23772 | 32.538037 | 438.15427 | 8.8152422 | 20.41116 | 3.2228163 | 3.5811922 | 305.75117 | 90.90283 | 18071.49988 |
| Acidification | kg SO2 ec | 14664.675 | 67766.337 | 187761.82 | 4720.0434 | 44367.863 | 188357.85 | 6718.1593 | 974.83917 | 13127.096 | 264.10454 | 611.51809 | 96.555535 | 107.29247 | 9160.301 | 2723.4476 | 541421.9021 |
| Eutrophication | kg PO4--- | 3849.1421 | 17787.115 | 49283.189 | 1238.9036 | 11645.55 | 49439.632 | 1763.3634 | 255.87301 | 3445.5629 | 69.321409 | 160.50953 | 25.343622 | 28.161823 | 2404.3698 | 714.84278 | 142110.88 |

**12MW turbines**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Sm | DP CLV Smal | Idle CLV Small | DP HLP 1hr | Idle HLP 1h | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.20089235 | 0.34584576 | 0.9695708 | 0.06611757 | 0.30591387 | 1.0034005 | 0.04145966 | 0.0127499 | 0.06721113 | 0.0039841 | 0.009224969 | 0.0014566 | 0.001618545 | 0.1381864 | 0.0410842 | 3.208716381 |
| Abiotic depletion (fossil | MJ | 18630986 | 32074131 | 8.99E+07 | 6131819.1 | 28370802 | 9.31E+07 | 3845016 | 1182442.7 | 6233236.7 | 369491.03 | 855534.11 | 135084.4 | 150105.73 | 12815565 | 3810193.7 | 297580021.5 |
| **Global warming (GWP1** | **kg CO2 e** | **1275872.5** | **2196475.3** | **6157769.3** | **419914.4** | **1942866.9** | **6372622.4** | **263311.35** | **80975.109** | **426859.6** | **25303.193** | **58588.012** | **9250.7433** | **10279.422** | **877625.44** | **260926.68** | **20378640.35** |
| Ozone layer depletion ( | kg CFC-11 | 0.22989795 | 0.39578027 | 1.1095611 | 0.07566388 | 0.35008287 | 1.1482752 | 0.04744576 | 0.0145908 | 0.07691532 | 0.0045594 | 0.010556904 | 0.0016669 | 0.001852237 | 0.1581383 | 0.0470161 | 3.672002879 |
| Human toxicity | kg 1,4-DB | 168083.49 | 289363.74 | 811224.76 | 55319.539 | 255953.36 | 839529.52 | 34688.648 | 10667.664 | 56234.5 | 3333.4436 | 7718.387 | 1218.6933 | 1354.2115 | 115618.41 | 34374.49 | 2684682.856 |
| Fresh water aquatic eco | kg 1,4-DB | 132748.34 | 228532.59 | 640686 | 43690.055 | 202145.87 | 663040.43 | 27396.268 | 8425.067 | 44412.669 | 2632.6744 | 6095.7983 | 962.49494 | 1069.524 | 91312.667 | 27148.154 | 2120298.602 |
| Marine aquatic ecotoxic | kg 1,4-DB | 3.64E+08 | 6.27E+08 | 1.76E+09 | 1.20E+08 | 5.54E+08 | 1.82E+09 | 7.51E+07 | 2.31E+07 | 1.22E+08 | 7221065.9 | 16719941 | 2639992 | 2933558 | 2.50E+08 | 74463674 | 5815689105 |
| Terrestrial ecotoxicity | kg 1,4-DB | 682.80904 | 1175.4883 | 3295.4552 | 224.72571 | 1039.7646 | 3410.4382 | 140.91641 | 43.335472 | 228.44257 | 13.541517 | 31.354563 | 4.950723 | 5.5012414 | 469.67906 | 139.6402 | 10906.04281 |
| Photochemical oxidatio | kg C2H4 e | 444.49429 | 765.21812 | 2145.2718 | 146.2917 | 676.86486 | 2220.1233 | 91.733614 | 28.210479 | 148.7113 | 8.8152422 | 20.41116 | 3.2228163 | 3.5811922 | 305.75117 | 90.90283 | 7099.603874 |
| Acidification | kg SO2 ec | 13317.043 | 22925.925 | 64272.317 | 4382.8974 | 20278.862 | 66514.867 | 2748.3379 | 845.18559 | 4455.3886 | 264.10454 | 611.51809 | 96.555535 | 107.29247 | 9160.301 | 2723.4476 | 212704.0427 |
| Eutrophication | kg PO4--- | 3495.4197 | 6017.5316 | 16870.015 | 1150.4105 | 5322.7381 | 17458.633 | 721.37592 | 221.84191 | 1169.4377 | 69.321409 | 160.50953 | 25.343622 | 28.161823 | 2404.3698 | 714.84278 | 55829.95239 |

**Complete cable removal**

| Impact category | Unit | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1h | Idle SPIV 1hr | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel OSV | DP OSV 1hr | Idle OSV 1h | Travel CLV Lar | DP CLV Larg | Idle CLV Large | DP HLP 1hr | Idle HLP 1h | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.17926601 | 0.51368267 | 1.43179 | 0.05848862 | 0.38985314 | 1.4594567 | 0.05527954 | 0.0132352 | 0.09966918 | 0.0039841 | 0.008683423 | 0.0257702 | 0.01145432 | 0.1381864 | 0.0410842 | 4.429883686 |
| Abiotic depletion (fossil | MJ | 16625335 | 47639517 | 1.33E+08 | 5424301.5 | 36155426 | 1.35E+08 | 5126688 | 1227449.1 | 9243433.9 | 369491.03 | 805310.55 | 2389953.9 | 1062286.7 | 12815565 | 3810193.7 | 410832471.4 |
| **Global warming (GWP1** | **kg CO2 e** | **1138523.1** | **3262411.9** | **9093335** | **371462.74** | **2475967.3** | **9269047.3** | **351081.8** | **84057.204** | **633001.55** | **25303.193** | **55148.642** | **163666.94** | **72746.68** | **877625.44** | **260926.68** | **28134305.47** |
| Ozone layer depletion ( | kg CFC-11 | 0.20514912 | 0.58785011 | 1.6385172 | 0.06693343 | 0.44614161 | 1.6701786 | 0.06326101 | 0.0151462 | 0.1140598 | 0.0045594 | 0.009937168 | 0.029491 | 0.013108138 | 0.1581383 | 0.0470161 | 5.069487007 |
| Human toxicity | kg 1,4-DB | 149989.07 | 429790.26 | 1197956.3 | 48936.515 | 326184.03 | 1221104.6 | 46251.53 | 11073.699 | 83391.648 | 3333.4436 | 7265.2842 | 21561.489 | 9583.6504 | 115618.41 | 34374.49 | 3706414.419 |
| Fresh water aquatic eco | kg 1,4-DB | 118457.8 | 339438.12 | 946117.37 | 38648.895 | 257612.38 | 964399.38 | 36528.358 | 8745.744 | 65860.739 | 2632.6744 | 5737.9485 | 17028.75 | 7568.939 | 91312.667 | 27148.154 | 2927237.919 |
| Marine aquatic ecotoxic | kg 1,4-DB | 3.25E+08 | 9.31E+08 | 2.60E+09 | 1.06E+08 | 7.07E+08 | 2.65E+09 | 1.00E+08 | 2.40E+07 | 1.81E+08 | 7221065.9 | 15738408 | 46707534 | 20760564 | 2.50E+08 | 74463674 | 8029013316 |
| Terrestrial ecotoxicity | kg 1,4-DB | 609.30371 | 1745.9459 | 4866.4827 | 198.79582 | 1325.0642 | 4960.5187 | 187.88855 | 44.984918 | 338.76362 | 13.541517 | 29.513915 | 87.589682 | 38.931862 | 469.67906 | 139.6402 | 15056.64435 |
| Photochemical oxidatio | kg C2H4 e | 396.64387 | 1136.574 | 3167.9777 | 129.41189 | 862.58883 | 3229.1931 | 122.31149 | 29.284233 | 220.52798 | 8.8152422 | 19.212936 | 57.019037 | 25.343821 | 305.75117 | 90.90283 | 9801.558129 |
| Acidification | kg SO2 ec | 11883.445 | 34051.742 | 94912.571 | 3877.1785 | 25843.15 | 96746.584 | 3664.4505 | 877.35525 | 6607.0153 | 264.10454 | 575.61932 | 1708.2896 | 759.30056 | 9160.301 | 2723.4476 | 293654.5542 |
| Eutrophication | kg PO4--- | 3119.1329 | 8937.8043 | 24912.381 | 1017.6708 | 6783.2366 | 25393.768 | 961.83456 | 230.28571 | 1734.1906 | 69.321409 | 151.08692 | 448.387 | 199.29905 | 2404.3698 | 714.84278 | 77077.61143 |

**Floating Wind Farm**

| Impact category | Unit | Travel AHTS | DP AHTS 1hr | Idle AHTS 1h | Travel SPIV 1 | DP SPIV 1hr | Ops SPIV 1hr | Idle SPIV 1hr | DP HLP 1hr | Idle HLP 1hr | Travel OSV | DP OSV 1hr | Idle OSV 1hr | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 1.2391346 | 0.30710858 | 0.2119049 | 0.03051156 | 0.01017193 | 0.062812 | 0.01017193 | 0.1381864 | 0.04108409 | 0.0058821 | 0.001311437 | 0.0019921 | **2.060271667** |
| Abiotic depletion (fossil | MJ | 1.15E+08 | 28481600 | 19652304 | 2829677.3 | 943356.78 | 5825257 | 943356.78 | 12815565 | 3810185.7 | 545515.98 | 121624.13 | 184745.51 | **191071938.2** |
| **Global warming (GWP1** | **kg CO2 e** | **7869775.4** | **1950454.5** | **1345813.6** | **193779.73** | **64602.215** | **398920.65** | **64602.215** | **877625.44** | **260926.13** | **37357.595** | **8328.9677** | **12651.597** | **13084838.04** |
| Ozone layer depletion ( | kg CFC-11 | 1.4180455 | 0.35145007 | 0.2425006 | 0.03491694 | 0.0116406 | 0.07188104 | 0.0116406 | 0.1581383 | 0.04701597 | 0.0067314 | 0.001500787 | 0.0022797 | **2.357741423** |
| Human toxicity | kg 1,4-DB | 1036764.5 | 256952.95 | 177297.53 | 25528.549 | 8510.6983 | 52553.822 | 8510.6983 | 115618.41 | 34374.419 | 4921.491 | 1097.2585 | 1666.7218 | **1723797.048** |
| Fresh water aquatic eco | kg 1,4-DB | 818811.94 | 202935.32 | 140025.37 | 20161.84 | 6721.5469 | 41505.758 | 6721.5469 | 91312.667 | 27148.098 | 3886.8764 | 866.58867 | 1316.3372 | **1361413.889** |
| Marine aquatic ecotoxic | kg 1,4-DB | 2.25E+09 | 5.57E+08 | 3.84E+08 | 55301170 | 18436284 | 1.14E+08 | 18436284 | 2.50E+08 | 74463519 | 10661170 | 2376934.2 | 3610532.9 | **3734172144** |
| Terrestrial ecotoxicity | kg 1,4-DB | 4211.67 | 1043.8253 | 720.23944 | 103.70515 | 34.573186 | 213.49048 | 34.573186 | 469.67906 | 139.63991 | 19.992675 | 4.4574161 | 6.7707586 | **7002.616562** |
| Photochemical oxidatio | kg C2H4 e | 2741.7084 | 679.50826 | 468.8607 | 67.509868 | 22.506415 | 138.9778 | 22.506415 | 305.75117 | 90.90264 | 13.01481 | 2.9016839 | 4.4076211 | **4558.555783** |
| Acidification | kg SO2 ec | 82141.548 | 20358.059 | 14047.06 | 2022.5948 | 674.29191 | 4163.7732 | 674.29191 | 9160.301 | 2723.4419 | 389.92354 | 86.934412 | 132.05227 | **136574.2719** |
| Eutrophication | kg PO4--- | 21560.28 | 5343.5253 | 3687.0325 | 530.88493 | 176.98622 | 1092.8953 | 176.98622 | 2404.3698 | 714.84129 | 102.34602 | 22.818297 | 34.660705 | **35847.62658** |

# J Chain locker calculations

The chain locker capacity was calculated using the following formula, from [75]

$$S = 1.1 * d^2 * \frac{l}{2} * 10^{-5}$$

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