# CORNWALL FLOW ACCELERATOR

## WP4 Innovation in Low Carbon Design and Manufacturability
## Task 4 – Mooring and Anchoring Systems

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## DOCUMENT HISTORY

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# PREFACE

ORE Catapult is the UK's flagship technology innovation and research centre for offshore wind, wave and tidal energy. ORE Catapult is playing a leading role in the delivery of the offshore wind sector deal (partnership between UK Government and offshore wind industry), including the Offshore Wind Growth Partnership, focused on enhancing the competitiveness of UK supply chain companies for supplying into the domestic and export markets. ORE Catapult has developed and actively maintains technology roadmaps to co-ordinate R&D funding and activity across agreed industry priorities. This provides ORE Catapult with a unique broad and objective perspective on the UK and global offshore wind industry.

We are an independent, not-for-profit business that exists to accelerate the development of offshore wind, wave and tidal technologies. Our team of over 200 people has extensive technical and research capabilities, industry experience and track record.

Through our world-class testing and research programmes, we work for industry, academia and government to improve technology reliability and enhance knowledge, directly impacting upon the cost of offshore renewable energy. We organise our activities around key areas for future innovation and developing local Centres of Excellence that will support the transformation of our coastal communities. These areas include:

- Floating wind
- Marine energy
- Testing and demonstration
- Operations and maintenance

These Centres of Excellence champion innovation in robotics, autonomous systems, big data and artificial intelligence, balance of plant – especially foundations – and next-generation technologies.

To date, we have supported more than 800 SMEs, contributed to 328 active and completed research projects, and supported over 180 companies in their product development.

# EXECUTIVE SUMMARY

The Cornwall Flow Accelerator (CFA) work package 4 details innovation in low carbon design and manufacturability that lays the groundwork for development of low carbon strategies, across design, manufacturing and operations & maintenance. Within this work package, the goal of this specific task (task 4) is to analyse the carbon impact of mooring systems for Floating Offshore Wind (FOW) in the Celtic Sea to identify opportunities in the Cornwall Area for carbon emission reduction. This study focuses on the whole life cycle of the mooring systems, i.e. from “cradle to grave”.

The aim of this life cycle analysis (LCA) study is to conduct a comparison between the total greenhouse gas (GHG) emissions generated as a result of the embodied carbon ($CO_2$) from the different types of mooring configurations currently available and identify what potential carbon emission reductions are available through optimisation and development.

A series of base case mooring configurations are analysed, which are representative of the types of mooring configurations and components that have been used in FOW projects to date. These base case configurations include catenary, semi-taut and taut systems with steel chain and synthetic rope mooring lines considered. Variation in other mooring components such as anchors and ancillaries are also analysed. Specific Celtic Sea FOW site characteristics such as water depth and seabed conditions are used to inform the mooring configurations. The results from the carbon LCA for the base case mooring configurations identify the key contributors to the mooring system carbon emissions. These findings are used to inform the second stage of the carbon LCA, where a series of alternative mooring configurations are analysed and compared to the base case configurations. These alternative configurations include further development of mooring system components such as anchor type selection and the introduction of load reduction devices (LRDs).

The results indicate that, for the base case mooring configurations considered, steel chain represents the highest proportion of carbon equivalent emissions ($TeCO_2e$) in the mooring system.

The study recommends the following key adaptations to the mooring system to reduce carbon footprint (where applicable):

- Reducing and replacing steel chain content with synthetic rope and supporting ancillaries such as buoyancy, ballast and load reduction devices (LRDs).
- Transitioning away from catenary mooring configurations to shorter and lighter semi-taut and taut systems.
- Exploring different anchor solutions, capable of withstanding greater load from the mooring line with variable direction of loading, to enable a reduction in mooring line material and overall mooring system carbon emissions.

The study recommends the following key adaptations to the manufacturing and supply chain processes to reduce carbon footprint:

- Utilising raw materials and components manufactured with recycled or “green” materials and clean energy sources.
- Reducing imports and transportation distance of finished components.

# CONTENTS

# NOMENCLATURE

| | |
|---|---|
| AHV | Anchor Handling Vessel |
| CFA | Cornwall Flow Accelerator |
| CoE | Centre of Excellence |
| $CO_2$ | Carbon Dioxide |
| CTV | Crew Transfer Vessel |
| DEA | Drag Embedment Anchor |
| EIA | Environmental Impact Assessment |
| FOSS | Floating Offshore Substation |
| FOW | Floating Offshore Wind |
| FOWT | Floating Offshore Wind Turbine |
| FPSO | Floating Production Storage and Offloading |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| IPCC | Intergovernmental Panel on Climate Change |
| KPI | Key Performance Indicators |
| LCA | Life Cycle Assessment |
| LRD | Load Reduction Device |
| ORE | Offshore Renewable Energy |
| O&G | Oil and Gas |
| O&M | Operations and Maintenance |
| ROV | Remotely Operated Vehicle |

| | |
|---|---|
| SOV | Service Operating Vessel |
| $TeCO_2e$ | Tonnes of $CO_2$ Equivalent |
| TLP | Tension Leg Platform |
| UHC | Ultimate Holding Capacity |
| VLA | Vertically Loaded Plate Anchor |

# 1 INTRODUCTION

The Cornwall Floating Offshore Wind Accelerator (CFA) is a collaborative research project which aims to drive and support the development and industrialisation of floating offshore wind (FOW) projects in Cornwall and the wider South-West region. The Celtic Sea region has significant potential FOW capacity which can help to support the UK's Net Zero targets, and most recent ambitious FOW targets of 50GW by 2030 [1].

As the demand in offshore wind turbines increases so too does the demand for materials and manufacturing. One of the most important design considerations for FOW is the mooring system. Additionally, there is now a key industrial drive to increase FOW manufacturing and assembly capability within the UK as FOW developers need to satisfy local content targets and the UK seeks to grow the offshore wind (OW) supply chain capacity across various regions of the UK. This is particularly important in areas such as Cornwall where there is potential to support the rapidly increasing number of renewable energy projects in the Celtic Sea.

This carbon footprint analysis examines the conventional materials and mooring configurations that have been used in early FOW projects, and will assess the potential advantages offered by alternative materials and manufacturing processes. This highlights where new development could potentially reduce the carbon footprint for future FOW projects. Finally, a summary is presented to assess the greenhouse gas (GHG) emissions of the current, new materials and processes based on prior findings.

The report is structured as follows:

Section 2 – Provides an overview of life cycle analysis (LCA) methodology, the standards and scope behind the study and details key FOW and mooring system assumptions.

Section 3 – Provides an overview of current mooring configurations used on pre-commercial FOW arrays, analyses the Celtic sea metocean and seabed conditions, discusses the industry standards behind mooring design, and looks at the life cycle considerations for each mooring component.

Section 4 – Provides an overview of mooring and anchoring systems, including review of mooring configurations, key mooring components, ancillaries, supply chain capability, raw material considerations and manufacturing methods.

Section 5 – Details the parameters of the selected mooring configuration used for the carbon LCA.

Section 6 – Assesses the carbon emissions of the mooring components and configurations, comparing key combinations to identify areas of carbon reduction potential.

Section 7 – Contextualises the carbon emission assessment, discussing potential reduction opportunities and their applicability to the UK FOW market and challenge.

Where applicable, the study refers to relevant Offshore Renewable Energy (ORE) Catapult projects and deliverables as well as other publicly available sources, which provide additional detail on the subject matter. Definitions for specific mooring terminology used throughout the report can be found in Glossary (Table 32) detailed in the Appendix.

## 1.1 Objectives

The Offshore Renewable Energy Catapult has been tasked with characterising and assessing the GHG emissions associated with conventional FOW mooring and anchoring systems and present the potential of low carbon design solutions that could be harnessed throughout the development of FOW projects in the Celtic Sea region.

The objectives of this project include:

1. Calculate the carbon emissions from base case Celtic Sea FOW mooring and anchoring configurations.
2. Compare results from base case mooring configurations against possible design changes to evaluate the impact on carbon emissions.
3. Map out opportunities for carbon footprint reduction of FOW mooring and anchoring solutions.
4. Identify and discuss future carbon reduction opportunities relevant to the Celtic Sea.

## 1.2 Scope

This report undertakes a life cycle analysis for the carbon emissions of floating wind mooring and anchoring components in the UK. The work presented is intended to provide a best estimate of the configurations for mooring and anchoring systems and resulting carbon emissions. Current and innovative mooring components and ancillaries, as well as processes such as manufacturing, transport and installation are considered. Areas of uncertainty are noted, and some alternative cases are presented.

This report does not make an assertion on the technical capabilities of certain mooring configurations and innovative solutions, it purely sets out to estimate the carbon emissions associated with mooring components for UK FOW projects and highlight carbon reduction opportunities.

# 2 METHODOLOGY

This study calculates the carbon emissions for a range of mooring configurations for FOW to identify potential opportunities for carbon emission reduction. The carbon emissions generated from these different mooring configurations is calculated using an LCA, with the results measured in the form of tonnes of carbon dioxide equivalent ($TeCO_2e$) produced. The specific method used to complete the LCA included in this project is defined in the following section.

## 2.1 Life Cycle Assessment

LCA is a method used to quantify the environmental impacts of a project, product, or process from raw material acquisition to end-of-life management; otherwise known as “cradle to grave.” LCAs have many uses, such as providing a means to systematically compare inputs and outputs of two projects, products or processes, identifying which stages of a life cycle have the greatest environmental impacts, establishing a comprehensive base case to which future research can be compared, providing guidance in the development of new products; to verify a product’s environmental claims, and to provide information to decision makers in industry, government, and non-governmental organizations. LCA guidelines have been established by the International Organization for Standardisation (ISO) 14040 family of standards. [2]

The foundation underpinning any LCA is the data related to a material or process. To perform an LCA study, it is first necessary to determine the goal and scope (i.e., what is the purpose behind conducting the LCA and what is being included in the study) as stated in ISO14040 [2]and 14044 [3].The scope must define what the system boundaries are in the study and the Key Performance Indicator (KPI) must be declared. The aim of this LCA study is to conduct a comparison between the total greenhouse gas (GHG) emissions generated from the embodied carbon ($CO_2$) of the different types of mooring configurations currently available and what potential reductions are available through optimisation and development. These mooring configurations will consist of a variety of mooring line types, anchor types and accessories. The calculation of the GHG emissions is based on the 100 year-global warming potentials for different GHGs i.e., carbon dioxide, methane and nitrogen oxide, as listed in the Intergovernmental Panel on Climate Change (IPCC), and are recorded in embodied carbon equivalent ($CO_2e$). The mass of $CO_2$ equivalent to mass of material ($TeCO_2e$)

This study reviews the Global Warming Potential (GWP) over a period of 100 years which is one of the commonly used factors, generally referenced as “GWP100”. The different mooring configurations included are reviewed from the ‘cradle to grave’ boundaries with respect to several limitations and assumptions which are further detailed in Section 5. An LCA is considered a dynamic process rather than static because usually more detailed information on the product will be gathered later during its service life. This is also the case for components included in this analysis due to the limited publicly available manufacturing data. Assumptions used for these limiting factors are highlighted in section 7.3.

## 2.2 ORE Catapult LCA

The focus of this LCA is to give a comparison between a set of base case mooring configurations, which are estimated based on conventional mooring configurations, and a variety of optimised configurations, which can include different anchor choices, mooring line materials and ancillaries. The results and KPIs will be given in $TeCO_2e$ with each component’s emissions being identifiable. The term “carbon emissions” will be used throughout the analysis of this report to reference the “$TeCO_2e$” related to each component or mooring configurations.

An online subscription database (Ecoinvent) is utilised to calculate the GWP100 for each method, which reports embodied carbon values for a wide range of materials and processes. This database supplies figures from the IPCC which give the corresponding GWP100 value for each material or process. The “IPCC 2013” values from Ecoinvent are used as inputs to calculate the resultant carbon emissions involved during the manufacturing, processing and installation of the different mooring configurations.

### 2.3 Assumptions and Limitations

It is important all assumptions and limitations are recorded and stated clearly during an LCA study. The accuracy of an LCA is dependent on the level of detail available on the components and also, the quality of material match on the embodied carbon database with the material used for the component. When a material is not present in the database, and cannot be found through literature review, values from similar materials are used. The global assumptions and limitations in this study are as follows:

- System operations and maintenance has been omitted from the study due to the uncertainty of vessel operating times and lack of available detailed component maintenance strategies.
- The decommissioning values have been assumed to be equal to the installation emissions generated.
- All mooring configurations included in the study are expected to withstand the full design life of the FOWT (25 years), therefore no component reinstallations are assumed.
- The installation time for each mooring component has been calculated assuming the processes encounter no difficulties or delays.
- The specific transportation emissions related to different products have been omitted and instead a representative transportation route from Asia and Europe to the UK has been used.
- Welding distance required for a Drag Embedded Anchor (DEA) and suction bucket. were calculated based on the anchor footprint and diameter (where applicable). [4]
- The anchor masses have been calculated using the ABS report “Development of mooring-anchor program in public domain for coupling with substructure program for FOWTs” [5]
- A consistent fuel consumption per hour of operation has been assumed for a large-scale Anchor Handling Vessel (AHV) for mooring installation.
- The additional processes related to the different grades of steel chain (R3, R4 and R5) have been excluded from this study as the steel chain carbon emissions have been calculated solely on their size and mass.

## 3 MOORING AND ANCHORING SYSTEM OVERVIEW

The main function of the mooring system is to provide adequate station-keeping capacity to limit the offset excursion of the floating turbine and substructure when in position within the array. The mooring system can be thought of as a series of springs that provide stiffness when displaced, which act by providing a restoring force. The use of different mooring line materials and components dictates the response of the mooring system to the FOWT and environment.

## 3.1 Mooring Components

With the UK targeting 100GW of installed capacity for offshore wind by 2050, and 49GW of this capacity estimated to be floating offshore wind, there will be great demand on the supply chain to provide the wind farm components. A study of FOW mooring and anchoring system market projections carried out by ORE Catapult and First Marine Solutions (FMS) predicted the quantities of mooring and anchoring system components would be required to facilitate 49GW of installed FOW capacity in the UK. These are listed in Table 1.

With the Celtic Sea 2023 leasing round target FOW capacity of 4GW, there will be significant amounts of mooring system components required. Approximate quantities are included in Table 1.

Table 1: Market Projections for Floating Wind in the UK [6]

| Parameter | UK (2050 target) [6] | Celtic Sea Estimate (2023 leasing round) |
|---|---|---|
| FOW Capacity | 49 GW | 4 GW |
| Mooring Line Quantity | ~12,000 | ~1,000 |
| Mooring Line Length | >6,000 km | >500 km |
| Anchor Quantity | ~12,000 | ~1,000 |
| Buoy Quantity | >6,000 | >500 |
| Clump Weight Quantity | >17,000 | >1,400 |
| Load Reduction Devices | >5,000 | >400 |

## 3.2 Current Mooring Configurations for Pre-commercial Units

Table 2 shows a summary of mooring configurations deployed on pre-commercial FOW projects to date, this information is based on ORE Catapult market knowledge gained through various platforms and some elements may not be wholly accurate. A range of mooring designs are currently used, however, all but one demo project has used a catenary mooring configuration. While catenary mooring configurations using steel chain have been most common to date, it is anticipated that projects in future may use more taut and semi-taut mooring configurations with steel wire and synthetic rope for the mooring line material.

Table 2: Current Pre-commercial Mooring Configurations

| Project Name | Location | Typology | Turbine (MW) | Developer | Year | No. of Lines | Depth (m) | Mooring Type | Mooring Design | Anchor Type |
|---|---|---|---|---|---|---|---|---|---|---|
| Hywind Demo | NO | Spar | 2 | Equinor | 2009 | 3 | 220 | Catenary | Chain and steel wire | DEA |
| Hywind Scotland | UK | Spar | 6 | Equinor | 2017 | 3 | 105 | Catenary | Chain | Suction piles |
| Floatgen Demo | FR | Ideol Barge | 2 | BW Ideol | 2018 | 6 | 33 | Semi-Taut | Nylon rope, 50m end chains | DEA |
| Kincardine 1 | UK | Semi-sub | 2 | KOWL | 2018 | 4 | 70 | Catenary | Chain, HMPE rope, clumps | DEA |
| WindFloat Atlantic | PT | Semi-sub | 8.4 | Principal Power | 2019 | 3 | 100 | Catenary | Chain, HMPE rope | DEA |
| Kincardine 2 | UK | Semi-sub | 9.5 | KOWL | 2021 | 4 | 70 | Catenary | Chain, HMPE rope, clumps | DEA |
| Tetraspar | NO | Tetra-Spar | 4 | Stiesdal | 2021 | 3 | 200 | Catenary | Chain, HMPE rope, clumps | DEA |
| Hywind Tampen | NO | Spar | 8 | Equinor | 2022 | 3 | 280 | Catenary | Chain and wire | Suction piles |

## 3.3 Celtic Sea Site Conditions

The Crown Estate released its refined areas of search on 10th Oct 2022 for the proposed 4GW Celtic sea leasing rounds, see Figure 1. The metocean and seabed characteristics of three reference sites collated from the North, South and East of the Celtic sea area are detailed in Table 3.

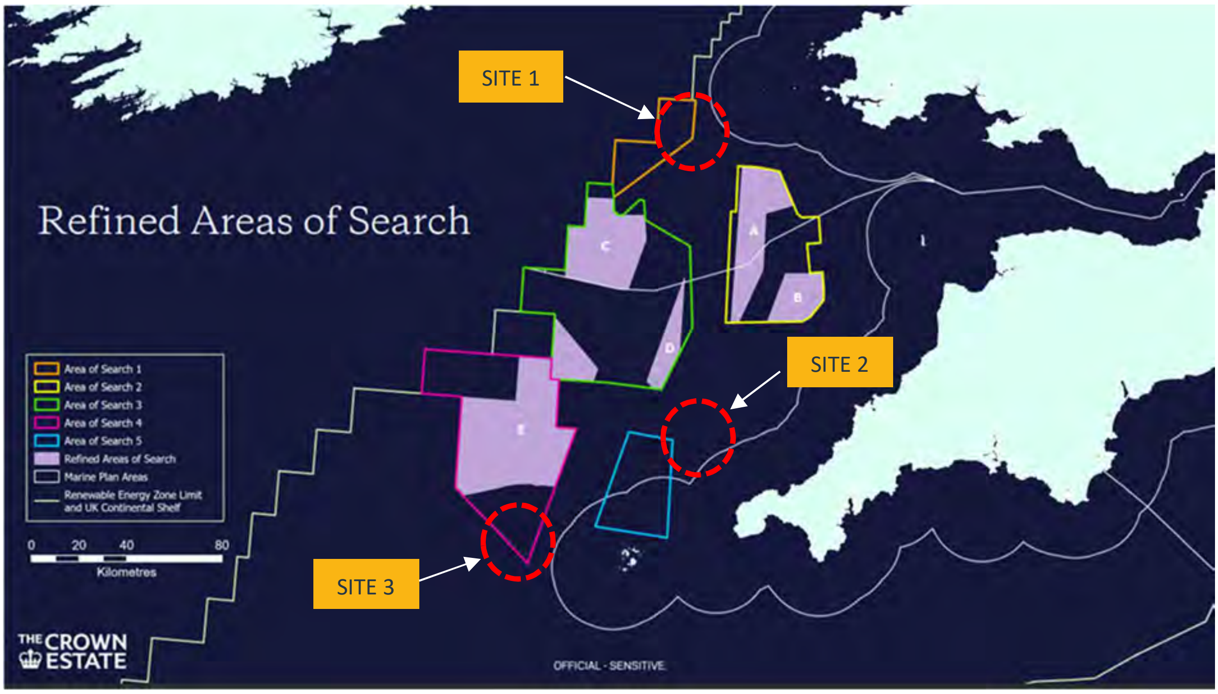


Figure 1: Celtic Sea Refined Seabed Leasing Areas and Reference Seabed Site Locations [7]

The reference site data was collated prior to the latest configuration of the Celtic sea leasing locations. However, the values are comparable to the latest refined areas, in terms of water depth and seabed conditions, and are therefore representative of areas proposed for development. Averages between the reference sites have been taken to inform mooring and anchoring design specification for the study. Table 3 shows values for the reference sites, data has been collated from ORE Catapult GIS Seabed Mapping.

Table 3: Reference Site Characteristics

| | Site 1 | Site 2 | Site 3 |
|---|---|---|---|
| **Water Depth Average (m)** | 107.7 | 72.3 | 113.5 |
| **Bedrock** | Chalk, Gneiss | Mudstone | Chalk, Mudstone |
| **Sediment** | Sand, Muddy Sand | Gravelly Sand, Gravel | Muddy Sand, Gravelly Sand, Sand |

## 3.4 Mooring Design Requirements

The design of the base case mooring systems have be predominantly based on DNV recommendations found in DNVGL-ST-0119 [8]. Additional considerations are detailed below:

1. Target overall FOWT structure excursion limit from the static equilibrium of the unloaded system to be within 30% of assumed water depth [9].

2. The system footprint, or the overall extent of the mooring system in spatial terms will use a turbine spacing of 10 rotor diameters (15MW turbine).

    - For this study a non-directional spread is assumed, therefore this applies along all mooring line directions.

3. Operational aspects such as restricting the use of fibre ropes to not interact/touch the seabed, ensuring technical requirements such as anchor uplift are maintained.

4. No snatch loading due to temporary slack in the mooring system. All lines to remain under tension.

5. During installation there will be tensioning required during install and handling of mooring lines.

    - All pretensions within 200-300te range allowing tensioning by direct use of vessel winch.

This study includes the level of detail required to establish realistic estimates of mooring system component sizes and quantities. The designs are based on industry knowledge and in-house ORE Catapult design expertise. The systems are estimated purely to inform carbon emissions analysis and are not approved mooring system designs for industry use.

## 3.5 Life cycle Stages

Key areas of consideration for each life cycle stage are illustrated in Figure 2, it highlights the key inputs and processes analysed. The life cycle stages highlighted in green show what has been included in our carbon calculations whereas the stages highlighted in red show what has not been included. The justification for not including the final two sections is explained in the Assumptions and Limitations (Section 2.3).

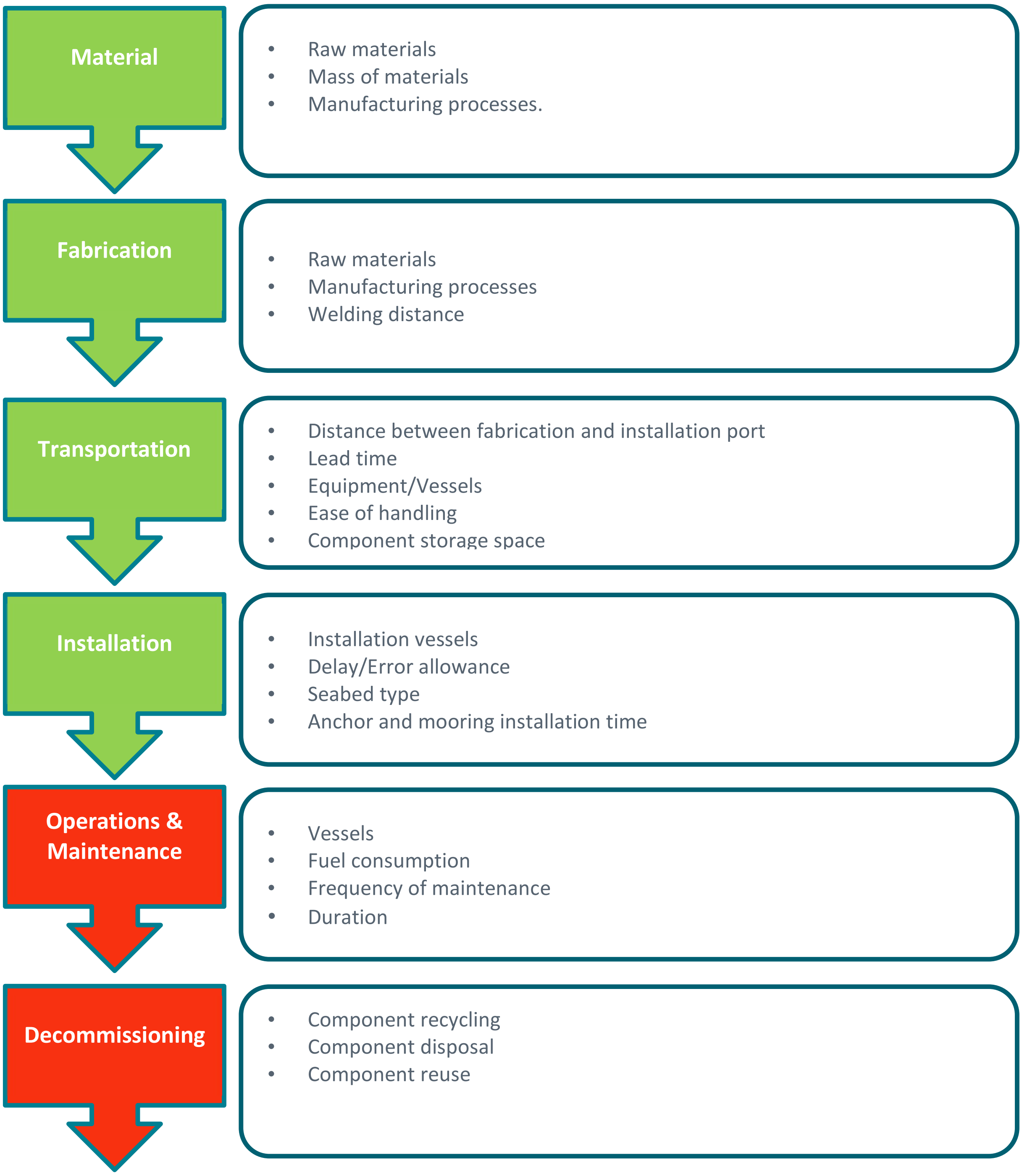


Figure 2: Life cycle Review

# 4 MOORING COMPONENTS AND ANCILLARIES

The mooring components and ancillaries used in current FOW projects are detailed in the following section, along with additional ancillary equipment identified to have potential for carbon emission reduction in the system. The relevant processes for the carbon LCA have been identified for each mooring component and ancillary.

## 4.1 Mooring Lines

The carbon emissions of three main types of mooring line are investigated in this report:

1. Steel Chain
2. Steel Rope
3. Synthetic Rope

### 4.1.1 Steel Chain

Steel chain is the most common mooring line type and has the longest history of use in offshore environments. Steel chains come in different sizes and strengths to suit a variety of applications, with chain diameter ranging from approximately 25mm to 220mm and steel strengths available for offshore application in grades such as grade R3, R4, R5, R3S and K3. There are two fundamental types of steel chain used; studlink and studless. Studlink chain includes a stud insert which is either pressed or welded into place across the middle of the chain link. The stud feature resists kinking and increases the robustness of the chain, making it suitable for regular reuse in applications such as rig moves. However, the stud feature has little benefit for permanent mooring application and adds unnecessary weight to the mooring system. For this reason, the studless chain was developed to simplify the chain for permanent moorings. It is, therefore, the studless chain that will be analysed in the carbon emissions assessment. A typical studless chain for offshore mooring is shown in Figure 3.

Figure 3: Steel Chain [10]

Steel chain can be used in all three sections of a catenary mooring system. It is the most commonly used line type at the seabed section because of the additional weight to aid the horizontal loading of the ground chain, and also because it has strong resistance to seabed abrasion. Steel chain is also suitable for use in the water column and near the water surface due to its bending properties in a dynamic environment. However, its use in the water column is limited to shallow waters, as the weight of the chain in deep water induces significant vertical load into the system.

Due to the common use and significant size of steel chain in mooring systems for floating offshore wind, it is important to understand the impact in terms of carbon emissions. The typical manufacture process for steel chain is detailed in Figure 4.

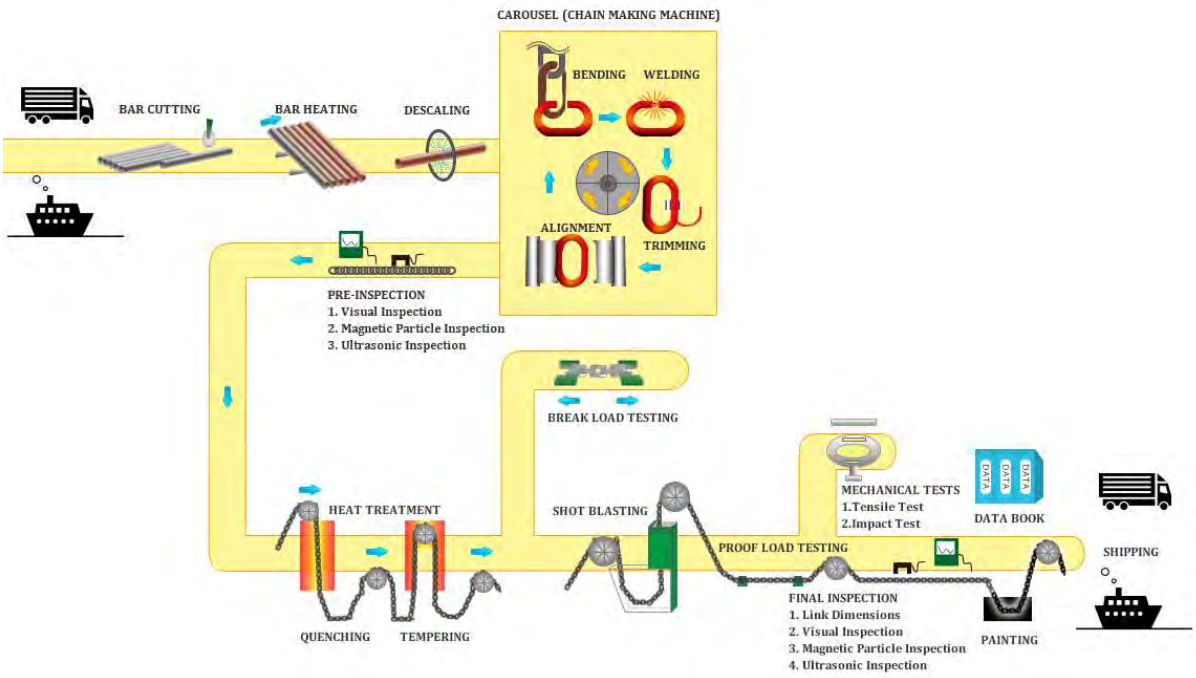


Figure 4 : Steel Chain Manufacturing Process Diagram (Adapted) [11]

**Key Points:**

- Steel chain is fabricated from steel bar, cut to length, bent into shape and welded
- One steel chain link can weigh up to 850 kg
- Suitable for application in all sections of a catenary system mooring line

### 4.1.2 Steel Wire Rope

Steel wire is lighter than chain with the same breaking load and a higher elasticity. These properties make steel wire a suitable option for deep water catenary to reduce the weight of the mooring line. Despite having the same breaking load as steel chain, steel wire suffers more from fatigue, torsion, bending and abrasion in dynamic environments, which can lead to failure in the mooring line. For these reasons, steel wire may be unsuitable for shallow water mooring systems where dynamic effects are typically more prevalent than in deep water. A protective sheath made from polyurethane or polyethylene can be used for corrosion protection to extend the design life. A typical spiral strand steel wire is shown in Figure 5.

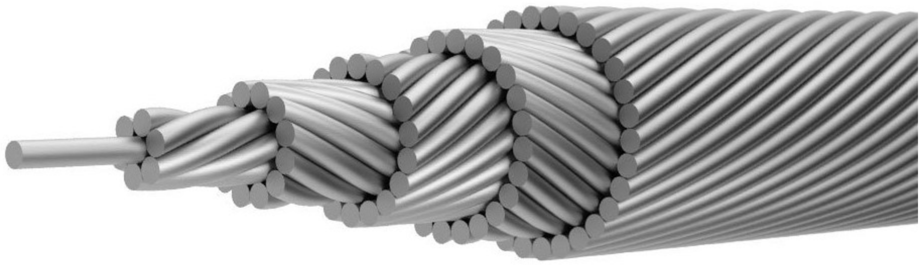

Figure 5: Spiral Strand Steel Wire [12]

Steel wire comes in a range of construction types including stranded, typically used for cranes and lifting equipment, and spiral stranded, typically used for deep water mooring lines. The spiral strand construction consists of individual steel strands counter-wound around each layer, giving a more uniform axial stiffness. A typical wire spiralling machine is shown in Figure 6.

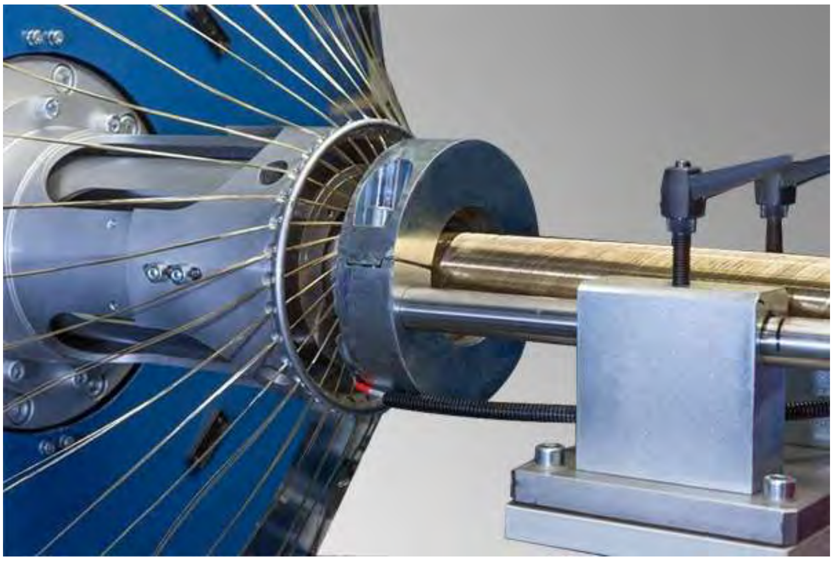

Figure 6 : Wire Spiralling Machine [13]

Alternatives to steel wire in mooring systems, such as synthetic rope, are likely to become more common as floating offshore wind commercialisation increases. However, alternative materials are currently less mature technologies, so it is important to understand the impact on carbon emissions when using steel wire in the mooring system.

**Key Points:**

- Steel wire is fabricated from steel strands
- One metre length of steel wire can weigh up to 60kg
- More suitable for deep water mooring application
- Not suitable for ground chain application at the seabed

### 4.1.3 Synthetic Rope

Natural material ropes have almost all been replaced by synthetic ropes in the Oil & Gas industry, which offer a more novel mooring line option. Synthetic rope has been identified as a technology with potential for cost reductions, such as reduced material and installation vessel requirements in floating offshore wind but requires further development before it becomes can be deployed at commercial scale. A typical synthetic rope construction is shown in Figure 7.

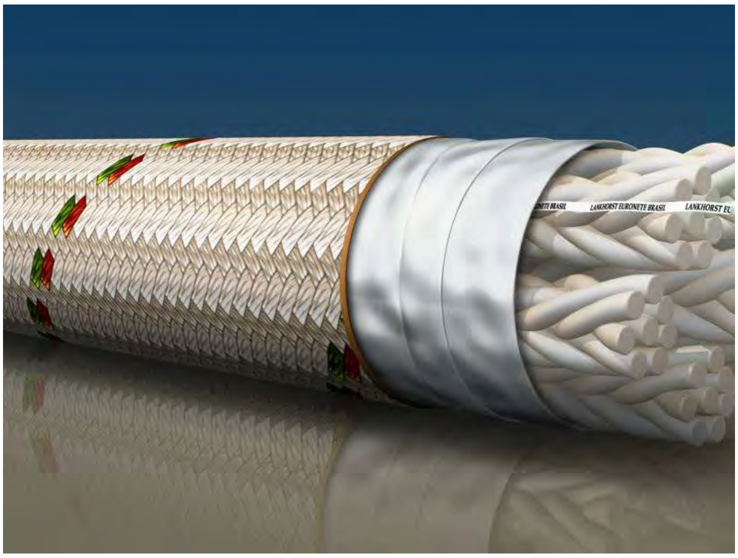

Figure 7 : Synthetic Rope Construction [14]

Similar to steel wire rope construction, synthetic ropes are woven from synthetic fibre strands and come in a range of construction types, including spiral stranded and braided. A typical industrial rope braiding machine is shown in Figure 8.


Figure 8 : Rope Braiding Machine [15]

There are currently several different materials that can be used for synthetic rope, including polyester, nylon and high modulus polyethylene (HMPE). The most common synthetic material used for mooring application is polyester due to its high strength and high resistance to load and degradation. Having very low elasticity, polyester does not stretch and is therefore less affected by line tension. These mechanical properties make polyester rope an attractive option for a taut mooring configuration for a semi-submersible or tension leg platform (TLP) substructure. Nylon rope has higher elasticity than polyester rope, and therefore is a potential option for reducing load in the mooring system at shallow sites with more onerous hydrodynamic loading conditions. Synthetic rope is also an attractive option for deep water floating offshore wind farms, as it is less cost sensitive to water depth than steel rope or chain.

These benefits of deploying synthetic rope within the mooring system indicate that it will be more commonly used in floating offshore wind as the technology develops, and it is therefore important to understand the carbon emission impact compared to the other mooring line types currently available.

**Key Points:**

- Synthetic rope is woven from fibre strands
- One metre length of synthetic rope can weigh up to 50kg
- More suitable for deep water mooring application and taut systems
- Not suitable for ground chain application in the seabed section

### 4.1.4 Mooring Line Emissions

Mooring line selection is primarily down to the mooring line configuration, water depth, hydrodynamic loads and substructure type used. Table 4 below highlights the key areas influencing the carbon emissions associated with mooring lines that have been considered for the carbon LCA.

Table 4 : Mooring Line Emission Summary (considered for the carbon LCA)

| Life cycle Stage | Mooring Line Type | Description |
|---|---|---|
| Raw Material | Steel Chain | Steel production, typically using a blast furnace, is a $CO_2$ and energy-intensive process.<br>This is particularly the case for large diameter steel bars. |
| | Steel Wire | Steel production, typically using a blast furnace, is a $CO_2$ and energy-intensive activity.<br>Steel production for wire strands is less energy-intensive than for large diameter steel bar. |
| | Synthetic Rope | The process of producing synthetic strands through polymerisation, drawing and stretching, texturing, intermingling and heat setting is a $CO_2$ and energy-intensive process. |
| Manufacture / Fabrication | Steel Chain | The carousel equipment used to make the steel bars into chain links, as described in Figure 4, is an energy-intensive process. Despite being mature technology, the conventional carousel process can be $CO_2$ intensive. |
| | Steel Wire | Wire strands are woven to create a spiral configuration for offshore application.<br>Larger diameter spiral steel wire rope requires energy-intensive machinery to weave. |
| | Synthetic Rope | Synthetic strands are woven to create braided rope configuration.<br>Larger diameter braided synthetic rope requires energy-intensive machinery to weave. |
| Transportation and Installation | Steel Chain | Large diameter chain is often produced in Asia and transported using large cargo ships (storing chain loose on deck) to the UK, which is significantly $CO_2$ and energy-intensive.<br>Installation of the chain may take longer due to the significant weight of the chain. |

| Life cycle Stage | Mooring Line Type | Description |
|---|---|---|
| | Steel Wire | While there is some capacity in the UK to manufacture steel wire strands and produce braided wire rope, the size and quantity required for commercial FOW relies on import from Asia. This transportation requires large cargo ships (storing steel wire on reels) and is $CO_2$ and energy-intensive.<br>Steel wire mooring lines are typically installed using AHVs along with sections of steel chain mooring line connected to anchors. |
| | Synthetic Rope | Synthetic rope can be produced in the UK and in the rest of Europe, however there is currently a lack of capacity to facilitate all planned commercial FOW projects.<br>Synthetic rope mooring lines are typically installed using AHVs along with sections of steel chain mooring line connected to anchors. |

Table 5 below highlights the key areas influencing the carbon emissions associated with mooring lines that have not been considered for the carbon LCA. These have been provided for reference.

Table 5 : Mooring Line Emission Summary (not considered for the carbon LCA)

| Life cycle Stage | Mooring Line Type | Description |
|---|---|---|
| **Operations** | Steel Chain | Operations activities may include maintenance, monitoring, and possible component replacement. These activities require vessels such as service operating vessels (SOVs) and AHVs to perform, however it is anticipated that minimal operations and maintenance (O&M) activities should be required for steel chain as it is mature and robust technology. |
| | Steel Wire | Operations activities may include maintenance, monitoring, and possible component replacement. These activities require vessels such as SOVs and AHVs to perform, however it is unclear to what extent these activities will be required for sections of steel wire in FOW projects, based on the limited O&M related activities in FOW demonstrations to date. |
| | Synthetic Rope | Operations activities can include maintenance, monitoring, and possible component replacement. These activities require vessels such as SOVs and AHVs to perform, however it is unclear to what extent these activities will be required for sections of synthetic rope in FOW projects, based on the limited O&M related activities in FOW demonstrations to date. |
| **Decommissioning** | Steel Chain | The process to remove steel chain at the end of service will likely require similar vessel resources to the installation process.<br>Steel chain has the potential to be reused repurposed, or recycled, however the mechanisms and feasibility to do so is not yet clear. The process of recycling steel components of this magnitude is currently highly $CO_2$ and energy intensive. |

| Life cycle Stage | Mooring Line Type | Description |
|---|---|---|
| | Steel Wire | The process to remove steel wire mooring lines at the end of service will likely require similar vessel resources to the installation process.<br>Steel wire has the potential to be reused repurposed, or recycled, however the mechanisms and feasibility to do so is not yet clear. The process of recycling steel wire is currently $CO_2$ and energy intensive. |
| | Synthetic Rope | The process to remove synthetic rope at the end of service will likely require similar vessel resources to the installation process.<br>Synthetic rope has the potential to be reused repurposed, or recycled, however the mechanisms and feasibility to do so is not yet clear. The processes to recycle synthetic materials are in development, but this is not currently a commercially available option. |

## 4.2 Anchors

Developing anchoring solutions for floating wind is not as simple as reusing technology from the offshore oil and gas (O&G) industry. Typically one or two large platforms must be anchored at a site and the anchoring makes up a very small proportion of the floating production costs, which can therefore be designed with a significant factor of safety. In contrast, commercial scale floating wind will require hundreds of anchors that will increase CAPEX of the mooring system.

There are several anchor types on the market with different capabilities depending on the seabed conditions and mooring configuration. The Celtic Sea has a seabed of variable hardness and sediment types, this creates anchoring challenges and may require various anchor types across the array.

The properties and manufacturing methods of the five most common anchor types are investigated below, a diagram of each type can be seen in Figure 9:

1. Gravity Anchors
2. Drilled/Driven Pile Anchors
3. Drag Embedment Anchors (DEAs)
4. Suction Bucket Anchors
5. Vertically Loaded Plate Anchors (VLAs)

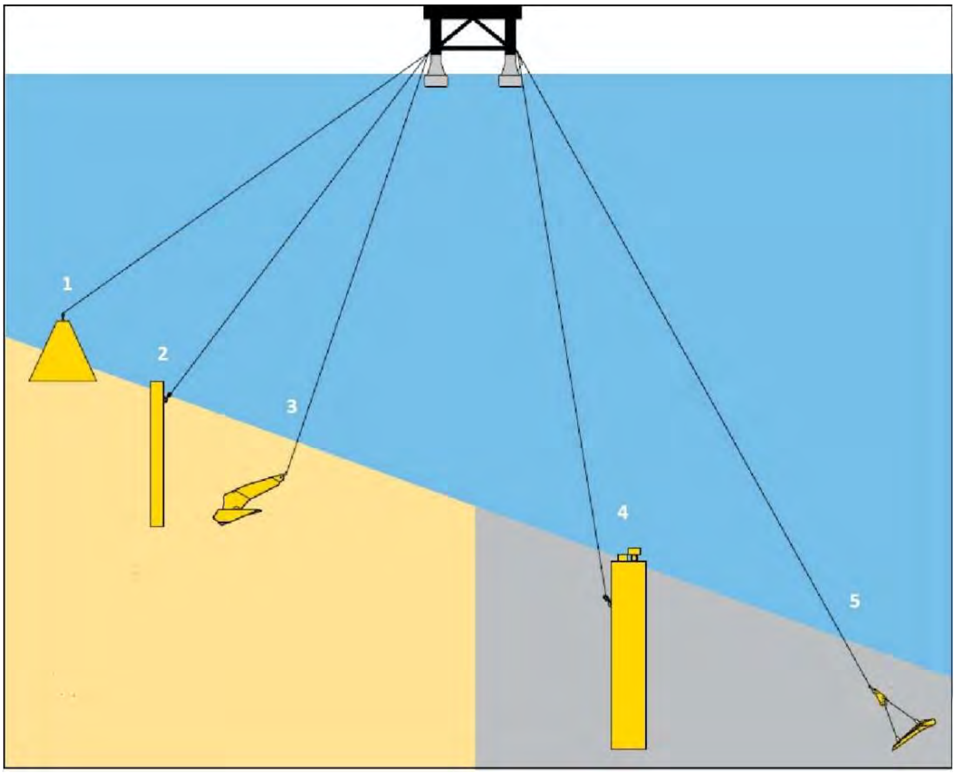


Figure 9: Visual Representation of Anchor Types [16]

### 1. Gravity Anchors

A gravity anchor is a mass of sufficient weight to adequately resist the loads applied from the turbine structure, with an acceptable factor of safety. The heavy dead weight resists force in the vertical or horizontal direction. The material of the anchor is cheap, but a large amount of material is needed to achieve the demanded capacity.

Figure 10: Gravity Anchor Rebar Structure [17]

Gravity anchors are constructed by slip forming concrete around steel rebar framework. Figure 10 shows the stages, from front to back. The difference between the gravity anchors weight and its buoyancy defines the load carrying capacity. Concrete gravity anchors require significantly more material mass than other anchor types to achieve the equivalent holding capacity. However, with concrete as the primary material, these anchors can be a cost effective solution and can allow for quayside construction.

Key Points:

- Poor holding value to weight ratio
- Large volumes of material required
- Easy to manufacture

**2. Drilled/Driven Pile Anchors**

Embedded anchor piles (driven or drilled) are needed for situations where a large holding capacity is required. Anchor piles can accommodate three types of mooring configurations—vertical tethers, catenary moorings, and semi-taut/taut moorings as commonly used on O&G Floating Production Storage and Offloading (FPSO) vessels. Anchor piles consist of hollow steel pipes that are either driven, or inserted into a hole drilled into the seabed and then grouted. Installation method is dependent on the seabed landscape.

Figure 11: Pile Manufacture

Piles are manufactured by rolling steel plate sections which are then seam welded, multiple sections are joined via circumferential welding. Figure 11 shows an operator removing welding slag after an external weld pass, the pile is on a roller-bed which can rotate at a set speed whilst being welded.

Key Points:

- Complex installation process. (Requires custom vessels and equipment)
- Can be driven or drilled, dependant on required strength and seabed conditions.
- High loading capability in all directions.

**3. Drag Embedment Anchors (DEAs)**

DEAs are buried within the seabed by pulling the anchor towards its indented connection point using a line attached to an AHV, the fluke section will be angled when pulled horizontally which penetrates the seabed sediment and embeds the anchor assembly until required tension is achieved. The simple installation method and mature technology makes DEA's is a cost-effective option for anchoring offshore structures. DEAs are one of the most efficient types of anchors, with holding capacities much greater than their weight. They are ideally suited to catenary line systems and have been used across the marine industry. They work to resist horizontal loading. A disadvantage is the uncertainty around the security of the embedment.


Figure 12: Anchor Production Line [18]

DEA anchors are normally manufactured in two parts; the fluke and the shank. Depending on the design some parts are cast and others are fabricated out of steel plate and welded. Designs are mature but DEAs can have more complex shapes which can make manufacturing a very manual process and hard to automate.

Key Points:

- Very popular and well known installation procedures.
- Only resists loads in the horizontal direction.
- Designs can be certified for local manufacture when IP is up – (newest design often still under licence).

### 4. Suction Bucket Anchors

Suction bucket anchors are inverted buckets that are embedded into marine sediment. Embedment is achieved through gravity and a negative pressure created by pumping water out.

Suction buckets are manufactured in the same way as piles, however they generally have a larger diameter and shorter length. Steel plate sections are rolled and then seam welded, multiple sections are joined via circumferential welding. Figure 13 shows a suction bucket being manufactured with a semi-automated column and boom welding system.

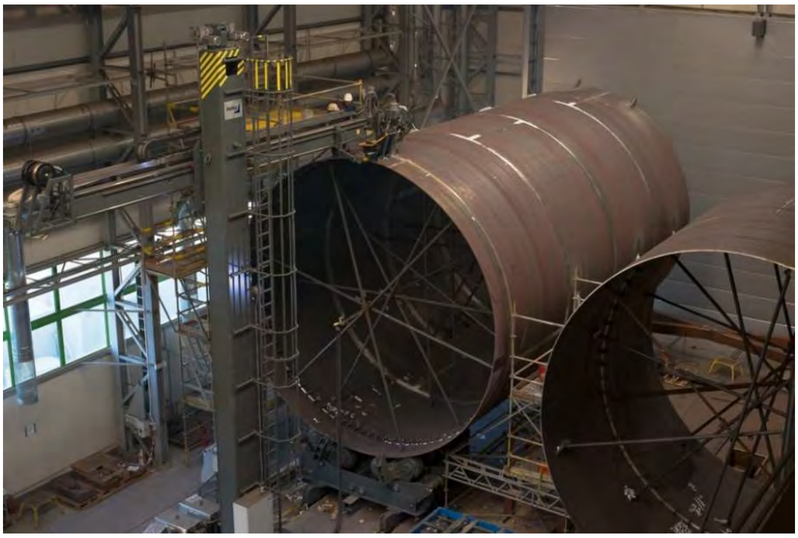

Figure 13: Suction Bucket Production with Semi Automated Weld Plant [19]

Suction buckets are in many cases easier to install than piles, which must be driven or drilled into the ground. Mooring lines are usually attached to the side of the suction caisson at the optimal load attachment point, which must be calculated for each anchor. Once installed, the suction bucket acts much like a short rigid pile and is capable of resisting both lateral and axial loads.

Key Points:

- Simple installation in soft clays and low strength sediments.
- Capable of resisting both lateral and axial loads
- Anchor can also be recovered by reversing the installation process.

5. **Vertically Loaded Plate Anchors (VLAs)**

VLA plate anchors are installed like a conventional DEA or can be embedded using a suction bucket. The anchor mode is changed from the installation mode to the vertical (normal) loading mode, the anchor can withstand both horizontal and vertical loads. Unlike DEAs, mooring lines can be in either a catenary or taut-moored configuration. For manufacturing the VLA is essentially a DEA but without the shank which is replaced with a chain system.

Key Points:

- Light weight, easy to install from a single AHV
- Primarily used in taut leg mooring systems, where the mooring line arrives at an angle at the seabed

### 4.2.1 Anchor Emissions

Anchor design selection primarily depends on the seabed type, mooring line configuration and the floating substructure used. However, there are possibilities to alter between different anchor types under specific conditions. Table 6 below highlights the key areas influencing the carbon emissions associated with anchoring.

Table 6: Anchor Emission Summary

| Life cycle Stage | Main Points |
|---|---|
| **Raw Material** | All designs considered except gravity anchors are wholly made using steel.<br><br>Concrete benefits from onsite production opportunities, however a significant amount of material is required. |
| **Manufacture** | Steel anchor designs use steel plate which is cast or cut from steel plate fabricated, rolled (applicable to piles and suction buckets) then welded.<br><br>Gravity Anchors are produced by casting wet concrete in a mould with rebar foundations. Anchors can either be solid or have sections to add ballast.<br><br>Anchor designs are mature and production processes are relatively standardised or streamlined, and therefore make up a small amount of overall emissions. |
| **Transportation and Installation** | Two key stages:<br><br>1. Raw material transportation to manufacturing location, and then to site.<br><br>Lighter anchors maximise vessel deck space is requiring fewer trips.<br><br>2. Installation/Commissioning.<br><br>Piles require specialist vessels with cranes, heave compensation systems and drilling/hammering equipment.<br><br>DEAs and VLAs require large bollard pull capabilities.<br><br>Gravity anchors require vessels with large cranes and deck space. |
| **Operations** | Anchor maintenance involves regular checks, length of life analysis, possible removal and exchange during maintenance. |
| **Decommissioning** | With differing installation methods some anchors are easier to recover than others. It will likely be an end of life decision on removal. |

The majority of emissions from anchoring come from raw material production, transport and installation. Table 7 summarises the general characteristics of the anchor designs analysed.

Table 7: Anchor Type Summary

| Anchor Type | Material | Weight Range (Te) | Installation Time (days/anchor) | Seabed Conditions | Load Direction | Shared Anchoring |
|---|---|---|---|---|---|---|
| **Gravity** | Concrete | 600 – 1000 | 1 | Any | Any | Y |
| **Piles** | Steel | 40 – 100 | 1.25 - 2 | Medium - Hard | Any | Y |
| **DEA** | Steel | 15 – 40 | 0.4 - 0.6 | Soft - Medium | Horizontal | N |

| Anchor Type | Material | Weight Range (Te) | Installation Time (days/anchor) | Seabed Conditions | Load Direction | Shared Anchoring |
|---|---|---|---|---|---|---|
| **Suction Bucket** | Steel | 60 – 100 | 0.75 – 1 | Soft - Medium | Any | Y |
| **VLA** | Steel | 10 – 30 | 0.4 – 0.6 | Soft | Vertical | N |

## 4.3 Mooring Ancillaries

Mooring product providers are developing their product ranges with a range of accessory solutions seeking to streamline mooring configurations whilst maintaining comparable performance. These products are designed to offer overall weight reduction, decreased installation time, lower costs, easier connection, disconnection and allow the use of smaller vessels.

### 4.3.1 Ballast

Ballast modules or clump weights are masses, each of several tonnes, that are attached to the mooring lines to tune the needed response. They can be fitted to the mid or upper-section of the mooring line to resist substructure uplift, to the mid-section to form a multi-catenary shape, and to the ground-section to convert vertical forces into horizontal forces at the anchor.

Controlling and limiting the forces at the anchor enables savings to be made to the anchor in terms of weight and design complexity. Clump weights fitted to the mid-section to form the catenary shape reduces the length of mooring line required. A reduction in the material used for anchors and mooring lines reduces fabrication, transport and installation resources and therefore can reduce the carbon emissions related to these activities.

Figure 14: Clump Weights Being Deployed [20]

Despite the benefits of installing clump weights, they come with their own carbon impact which must be considered. Clump weights are typically made from higher density materials such as cast iron, reinforced concrete or sand. The most common choice of material is cast iron due to its significantly higher density and superior mechanical characteristics, resulting in a product that achieves the target weight in less space and volume compared to other materials. Other materials such as steel have similar properties to cast iron but are far more expensive to manufacture. The type of cast iron most commonly used for clump weights is Grey iron EN-GJL-200. Clump weight castings can reduce the mining and extraction phases of manufacture.

### 4.3.2 Buoyancy

Buoyancy modules are flotation devices that can provide several tonnes of uplift and are directly attached to the mooring lines. They can be fitted to the lower section of the mooring line above the seabed to prevent damage to synthetic lines, or to the mid-section to form a semi-taut style shape. By preventing damage at the seabed section of the mooring line, buoyancy modules can reduce the need for O&M interventions and reduce the amount of ground chain.

Figure 15 - Buoyancy Modules [21]

Despite the benefits of installing buoyancy modules, the modules come with their own carbon impact which must be considered. Buoyancy modules are typically made of a low density polymer-based core with a polyethylene protective outer layer. The polymer-based core can be made from low-density polyurethane or from syntactic foam. The manufacturing process includes roto-moulding to produce the polyethylene outer-shell which is then filled polymer-based foam, which eventually sets within the module.

### 4.3.3 Load Reduction Devices (LRDs)

Load reduction devices (LRDs) are additional mooring line components that are typically installed between sections of mooring line in the water column. These devices come in various shapes and sizes with different functions to deliver a beneficial stiffness response and achieve reduction of load within the mooring system. By decreasing the maximum load in the mooring system, other mooring components such as steel chain, steel wire, synthetic rope and anchors can be reduced in load capacity, and therefore reduced in size. A reduction in load can also reduce the size of the floating substructure. While the manufacture and installation processes for LRDs vary and contribute their own carbon emission impact, these devices have the potential to reduce the overall carbon emissions for mooring systems.


Figure 16: Load Reduction Devices (Left: TFI Marine SeaSpring [22], Right: Dublin Offshore [23])

Various materials and manufacturing processes are used to produce LRDs. LRDs that stretch and compress are typically made from lower stiffness materials such as polymers. Other LRDs that include more complex hydraulic or gravitational features are typically made from steel or concrete.

### 4.3.4 Installation Aids

**Tensioners**

Tensioning systems can be used to speed up and improve the safety of installation and adjustment of mooring line tension. Both in-line and cross tensioning designs are available on the market. A cross tensioning device using opposing anchors is seen in Figure 17.


Figure 17: Stevtensioner System Diagram [16]

Repeatedly heaving up and slacking the active chain using a vessel crane in a yo-yo action builds up the horizontal load on the anchor. A vertical pull on the active chain can induce more than double that pull in the horizontal line. The equipment can also be used for two-way cross tensioning of opposing anchors, or three-way tensioning with the addition of a link plate, thereby reducing the number of operations [24]. Tensioners also allow activities to be performed by smaller, less-capable vessels.

**Connectors**

Quick connector systems have the potential to speed up installation and reconnection of the floating turbines mooring and dynamic cables systems, which is especially important when employing a tow to port strategy. Quick connectors can be deployed at the top or bottom end of the mooring line to connect straight into the substructure or provide connection to the anchor. Most designs on the market use a variation of ball and socket technology to provide a two-part, male/female connection, see Figure 18. Their employment on FOWTs may remove the need for expensive chain jacks, fairleads and pull-through connectors, this can eliminate the requirement for remotely operated vehicles (ROVs) or diver involvements. Avoidance of complex interventions can reduce emissions associated with installation and O&M.

Figure 18: First Subsea Mooring Connector [25]

### 4.3.5 Shared Anchors

Shared anchor systems are defined by multiple turbines or structures connected to one anchor. Hywind Tampen's 88MW array is currently the only example of shared anchors in floating wind, the project will use 19 anchors for 11 turbines, which is dramatically less than the earlier Hywind Scotland project that used 15 anchors on 5 turbines [24] . In these cases, anchors will need to resist multi-directional loading. Environmentally the use of shared anchors can have potential to reduce material requirements across the wind farm and, therefore, save time and vessel requirements from a transportation, installation and O&M perspective.

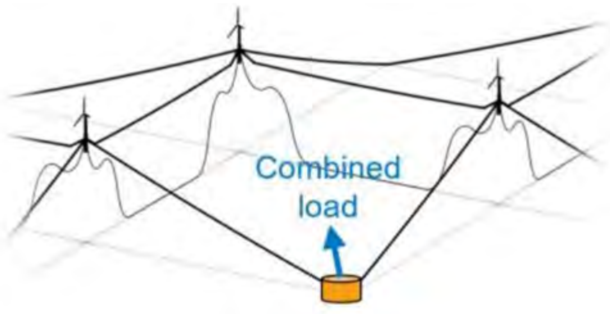


Figure 19: Shared Anchor Concept Geometries [26]

# 5 MOORING CONFIGURATIONS

The following mooring systems are estimated with reference to the design requirements and reference Celtic Sea site conditions from sections 1.1 and 3.4. Table 8 presents common assumptions for all base cases. The following sections include details on the Line, anchor and any ancillaries used. Overall summary tables for the base case and alternative mooring configurations are provided at the end of the section.

Table 8: Base Case Assumptions

| Parameter | Value |
|---|---|
| Wind Turbine Generator (WTG) Capacity | 15MW |
| Expected Design Life | 25 years |
| Substructure Type | Semi-Submersible |
| Water Depth | 100m |

## 5.1 Base Case Mooring Configurations

Base case configurations have been established based on existing configurations used in FOW to date. These base case configurations will provide a benchmark to compare alternative components or materials influence the carbon emissions associated with each system.. The six base case mooring configurations below are analysed:

- Chain Catenary (three line) – default case
- Chain Catenary (six line)
- Chain Catenary (nine line)
- Semi-Taut Mixed Synthetic Rope and Chain with Buoyancy Modules
- Semi-Taut Mixed Synthetic Rope and Chain with Clump Weights
- Taut Synthetic Rope

### 5.1.1 Three-Line Chain Catenary Configuration (Catenary A)

The catenary mooring is commonly employed in conventional shallow water environments and comprises of chain only between the anchor point and substructure. Station-keeping is achieved by a restoring force characterised by the weight of chain employed, as opposed to its strength. A typical catenary mooring system is shown in Figure 20, and the setup for the three-line mooring configuration is provided in Table 9. This base case configuration is the default case from which the other configurations are compared.

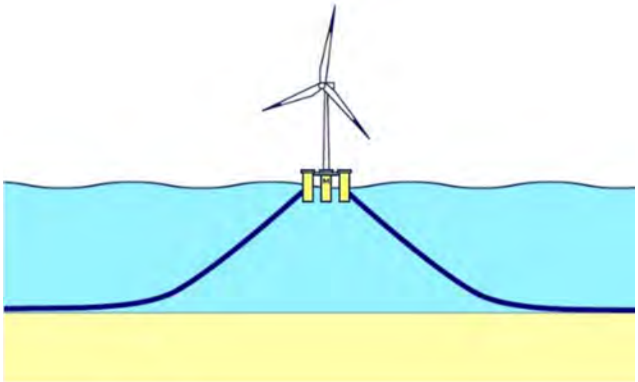

Figure 20: Typical Catenary Mooring System [6]

Table 9 : Three-Line Catenary Configuration (Catenary A)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain | 152 | 3 | 750 | 345 |
| Anchor (DEA) | - | 3 | - | 30 |

### 5.1.2 Multi-Line Chain Catenary Configuration (Catenary B & C)

Whilst a three-line configuration has proven popular for many developers of pilot farms (WindFloat Atlantic, and Hywind Scotland) some developers are considering introducing additional lines and are looking at six or even nine line scenarios. For example, the developer BW Ideol uses three clusters of two nylon mooring lines in their FloatGen project [27].

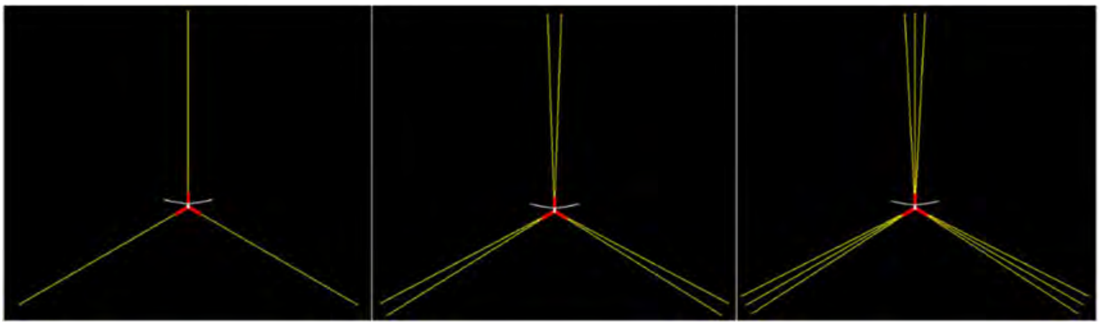

Figure 21: Example Layout of FOWT Mooring Configuration (Left: 3-Line, Middle: 3 by 2, Right: 3 by 3)

ORE Catapult in-house mooring system analysis has indicated that introducing additional mooring lines can reduce the size of mooring chain and the anchor capacity required for a plain catenary mooring configuration. These design optimisations have been included to show the impact on the carbon emissions of the mooring system for using multiple lines. The multi-line mooring configurations are shown in Figure 21, and the setup for the configurations are provided in Table 10.

Table 10 : Multi-Line Catenary Configurations (Catenary B & Catenary C)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| **Catenary B – Multi-Line Catenary Mooring Configuration** | | | | |
| Chain | 132 | 6 | 750 | 262 |
| Anchor (DEA) | - | 6 | - | 23 |
| **Catenary C – Multi-Line Catenary Mooring Configuration** | | | | |
| Chain | 112 | 9 | 750 | 188 |
| Anchor (DEA) | - | 9 | - | 12 |

### 5.1.3 Ballasted Catenary Configuration (Mixed Ballasted)

The ballasted catenary configuration includes multiple-tonne clump weights added to the midsection of each anchor cable to provide additional tension and therefore increased stiffness of the floating structure. This allows the section of steel chain in the water column to be partially replaced with synthetic rope. A typical ballasted catenary mooring system is shown in Figure 22, and the setup for the configuration is provided in Table 11.

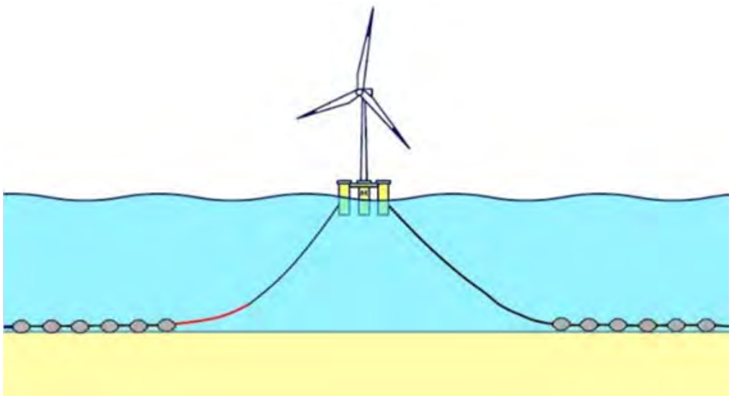

Figure 22: Typical Ballasted Catenary System [6]

Table 11: Ballasted Catenary Configuration (Mixed Ballasted)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain | 152 | 3 | 400 | 184 |
| Polyester Rope | 220 | 3 | 150 | 5 |
| Anchor (DEA) | - | 3 | - | 12 |
| Clump Weights | - | 10 per line | - | 10 |

### 5.1.4 Buoyant Configuration (Mixed Buoyant A)

The buoyant configuration employs a hybrid synthetic rope and chain line. Buoyancy modules are attached to the rope to prevent damage through contact with the seabed. Substructure stability is achieved predominantly due to visco-elastic properties of the rope, however, the anchor points can experience significantly increased vertical loads from the mooring lines. A typical buoyant semi-taut mooring system is shown in Figure 23, and the setup for the configuration is provided in Table 12.

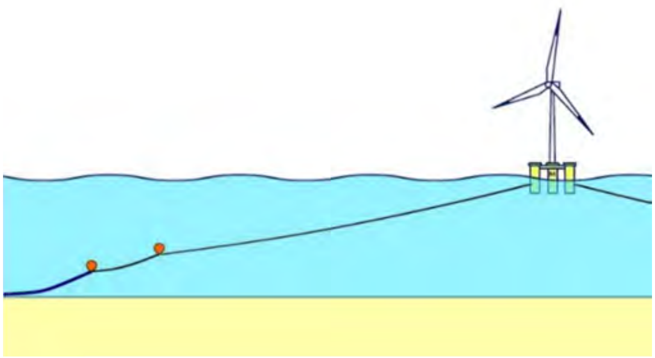

Figure 23 : Typical Buoyant Semi-Taut System [6]

Table 12: Buoyant Configuration (Mixed Buoyant A)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain | 152 | 3 | 400 | 100 |
| Polyester Rope | 230 | 3 | 150 | 5 |
| Anchor | - | 3 | - | 15 |
| Buoyancy Units | 3000 | 1 per line | 6 | 30 |

### 5.1.5 Taut Configuration (Taut A)

The taut configuration comprises synthetic rope tendons connected under tension to the anchor point, with short sections of chain and connectors that may be employed at the termination points to allow the adjustment of length and overall tension. Anchors used in taut configurations experience higher loads than catenary and semi-taut configurations, and therefore the anchor ultimate holding capacity (UHC) is increased accordingly. The anchor type selected must also be able to withstand vertical load in a taut configuration. The seabed type which results in the least carbon emissions for suction buckets is selected for this configuration. Further details on anchor selection across various seabed types are provided in Section 6.2. A typical taut mooring system is shown in Figure 24, and the setup for the configuration is provided in Table 13.

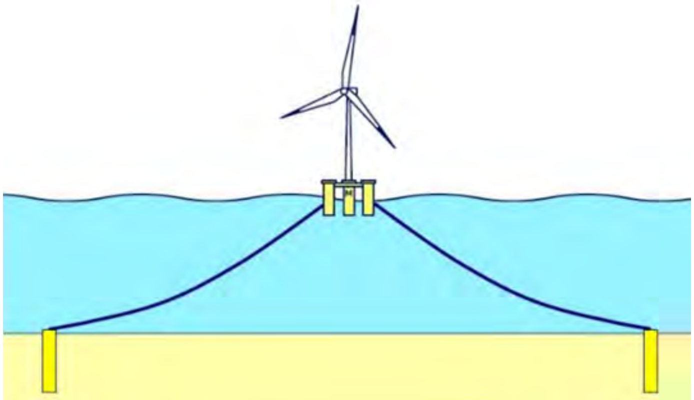

Figure 24: Typical Taut Mooring System [6]

Table 13: Taut Mooring Configuration (Taut A)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain | 152 | 3 | 50 | 23 |
| Polyester Rope | 200 | 3 | 350 | 10 |
| Anchor (Suction Bucket) | 4600 | 3 | 31 | 113 |

### 5.1.6 Base Case Configuration Summary

Table 14 summarises the components for each base case mooring configuration. Three, six and nine line configurations of the catenary system are selected to examine the effect of using multiple lines with smaller chain sizing and its impact on the carbon emissions. The buoyant, ballasted, and taut configurations are selected to examine the effect of using different mooring materials, component sizes and lengths, and their impact on the carbon emissions. The base cases selected in Table 14 are then compared against alternative mooring systems, detailed in Section 5.2, to analyse the effect of design and component changes.

Table 14 : Base Case Mooring Configuration Summary

| Configuration Name | Line Type | No. of Lines | Total Chain Length (m) | Chain Size (mm) | Rope Length (m) | Rope Diameter (mm) | Ancillaries | Anchor Type | Anchor Sizing (Te) |
|---|---|---|---|---|---|---|---|---|---|
| **Catenary A** | Chain | 3 | 750 | 152 | - | - | - | DEA | 30 |
| **Catenary B** | Chain | 6 | 750 | 132 | - | - | - | DEA | 23 |
| **Catenary C** | Chain | 9 | 750 | 112 | - | - | - | DEA | 12 |
| **Mixed Buoyant A** | Chain, Synthetic Rope | 3 | 400 | 152 | 150 | 230 | Buoyancy Modules | DEA | 15 |

| Configuration Name | Line Type | No. of Lines | Total Chain Length (m) | Chain Size (mm) | Rope Length (m) | Rope Diameter (mm) | Ancillaries | Anchor Type | Anchor Sizing (Te) |
|---|---|---|---|---|---|---|---|---|---|
| **Mixed Ballasted** | Chain, Synthetic Rope | 3 | 400 | 152 | 150 | 220 | Clump Weights | DEA | 12 |
| **Taut A** | Chain, Synthetic Rope | 3 | 50 | 152 | 350 | 200 | - | Suction Bucket | 113 |

## 5.2 Alternative Mooring Configurations

Alternative mooring configurations were adapted from the base case configurations to analyse the impact of specific component and system design changes on carbon emissions. The changes made are designed to allow the mooring system to maintain the station-keeping requirements, as detailed in Section 3.4. The following configurations were investigated.

- Catenary with reduced ground chain diameter
- Chain and Wire Catenary
- Chain and Synthetic Rope Catenary
- LRDs
- Shared Anchor Catenary
- Anchor Type by Seabed Conditions
- Optimised Mixed Buoyant

### 5.2.1 Catenary Mooring Configuration with Reduced Ground Chain Diameter (Catenary D)

Over engineering has been prevalent in the offshore wind industry as design choices are based on O&G experience. The size of steel chain used in the mooring line is typically conservatively large for the loads experienced. There is scope to optimise the ground chain section in a catenary configuration, as this typically experiences less load than the chain section in the water column. This reduced load can allow the reduction in diameter of the ground chain. The setup for this mooring configuration is provided in Table 15.

Table 15 : Catenary Configuration with Reduced Ground Chain Diameter (Catenary D)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain (Upper Section) | 152 | 3 | 300 | 138 |
| Chain (Ground Section) | 114 | 3 | 450 | 117 |
| Anchor (DEA) | - | 3 | - | 30 |

### 5.2.2 Chain and Steel Wire Catenary Mooring Configuration (Catenary F)

Steel wire has a higher strength-to-weight ratio than steel chain, this can reduce the weight of the mooring line. This can be an advantage for deep water mooring systems, where reducing the quantity of steel in the mooring line saves cost and reduces load in the system. However, adding a section of steel wire may not perform as required in shallower water depths, where greater elasticity is necessary. As shown in Table 2, steel wire sections have already been used in the mooring systems for current FOW projects such as the Hywind projects. The setup for this mooring configuration is provided in Table 16.

Table 16: Chain and Steel Wire Catenary Configuration (Catenary F)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain | 152 | 3 | 650 | 299 |
| Steel Wire | 130 | 3 | 100 | 7 |
| Anchor (DEA) | - | 3 | - | 25 |

### 5.2.3 Chain and Synthetic Rope Catenary Mooring Configuration (Catenary G)

The introduction of a short 100m section of polyester line allows the chain size to be reduced while maintaining sufficient ballast through the lower chain section. This type of system introduces an element of elasticity (through the polyester line) whilst negating any complications through additional jewellery (such as clump weights, buoys or load reduction devices). The setup for this mooring configuration is provided in Table 17.

Table 17: Chain and Synthetic Rope Catenary Configuration (Catenary G)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain | 112 | 3 | 650 | 163 |
| Polyester Rope | 195 | 3 | 100 | 3 |
| Anchor (DEA) | - | 3 | - | 25 |

### 5.2.4 Load Reduction Device (LRD) Configurations (LRD A, B, C & D)

The inclusion of LRDs into the mooring configuration can reduce the diameter of material required in the lines and anchors due to reduced load profiles. The mooring configurations detailed in Table 18 show potential optimisation offered by LRD technology. Benefits are seen through reductions in chain and anchor size, reduced in chain lengths and use of synthetic rope.

Table 18: Load Reduction Device Configurations

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| **LRD A - Catenary Configuration with Reduced Chain Diameter** | | | | |
| Chain | 81 | 3 | 750 | 98 |
| Anchor (DEA) | - | 3 | - | 20 |
| LRD | - | 3 | - | 295 |
| **LRD B - Catenary Configuration with Reduced Chain Length** | | | | |
| Chain | 152 | 3 | 350 | 161 |
| Anchor (DEA) | - | 3 | - | 20 |
| LRD | - | 3 | - | 295 |

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| **LRD C - Catenary Configuration with Reduced Chain Diameter and Synthetic Rope** | | | | |
| Chain | 81 | 3 | 250 | 33 |
| Polyester Rope | 195 | 3 | 100 | 3 |
| Anchor (DEA) | - | 3 | - | 20 |
| LRD | - | 3 | - | 295 |
| **LRD D - Taut Configuration** | | | | |
| Polyester Rope | 200 | 3 | 120 | 3 |
| Suction Bucket | - | 3 | - | 25 |
| LRD | - | 3 | - | 295 |

### 5.2.5 Shared Anchor Catenary Configuration (Shared Anchor)

Shared anchor configurations attach multiple mooring lines to anchors. Sharing anchors presents obvious savings due to the reduced material quantity, however there are trade-offs to consider. Firstly, the chosen anchor type must be able to cope with multi-directional loading, and therefore, it is unlikely that DEAs can be used. Secondly, shared anchors will likely increase mooring line length. However, with increased mooring line length on the seabed, there is potential to decrease line diameter to compensate for the increased material weight. The adoption of shared anchors can offer a 40% reduction in the total number of anchors required when considering a wind farm of at least 6 floating turbines, meaning a 40% reduction in anchor mass can also be estimated for this system [28]. These considerations have all been considered for the mooring system configuration, shown in Table 19.

Table 19: Shared Anchor Catenary Configuration (Shared Anchor)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain (Upper Section) | 152 | 3 | 300 | 138 |
| Chain (Ground Section) | 114 | 3 | 550 | 143 |
| Anchor (Suction Bucket) | 4300 | 1.8 | 28 | 88 |

### 5.2.6 Varying Anchor Type with Seabed Conditions (Catenary E and Taut B)

A significant factor in anchor selection is the seabed typology. While DEAs are generally the most cost effective anchor solution, they are not always suitable. DEAs are more easily installed in soft to medium conditions and they also require sufficient dragging distance along the seabed to be installed. Suction buckets are sensitive to seabed type as harder ground conditions present challenges to installation. For hard seabed conditions, driven pile anchors can be used.

Different anchor types and seabed conditions were assessed using the alternative catenary and taut mooring configurations to quantify their impact on carbon emissions, as defined in Table 20 and Table 21. For the Taut B configuration, the seabed type which resulted in the least carbon emissions for driven pile was selected. Further details on the seabed types is given in Section 1.1.

Table 20: Catenary Configuration with Driven Piles (Catenary E)

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain | 152 | 3 | 750 | 345 |
| Anchor (Driven Pile) | 1000 | 3 | 39 | 41 |

Table 21: Taut Configuration with Driven Piles (Taut B)

| Mooring Component | Diameter (mm) | Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain | 152 | 3 | 50 | 23 |
| Synthetic Rope | 200 | 3 | 350 | 10 |
| Anchor (Driven Pile) | 1000 | 3 | 39 | 41 |

### 5.2.7 Mixed Buoyant Semi-Taut Configuration with Reduced Chain Size (Mixed Buoyant B)

Mooring systems that use buoyancy modules have the potential to reduce the chain sizing as the buoyancy modules elevate the lines in the water column and reduce the amount of ground chain contact on the sea bed. For the configuration shown in Table 22, the ground chain section is reduced to 114mm and the total chain length has been reduced to 400m.

Table 22: Mixed Buoyant B Configuration

| Mooring Component | Diameter (mm) | No. of Lines/Quantity | Length (m) | Weight per Line (Te) |
|---|---|---|---|---|
| Chain (upper section) | 152 | 3 | 200 | 92 |
| Chain (ground section) | 114 | 3 | 200 | 52 |
| Polyester Rope | 230 | 3 | 150 | 5 |
| Anchor | - | 3 | - | 15 |
| Buoyancy Units | - | 1 per line | - | 30 |

### 5.2.8 Alternative Mooring Configuration Summary

Table 23 summarises the components for each of the alternative mooring configurations.

Table 23: Alternative Mooring Configuration Summary

| Configuration Name | Line Type | No. of Lines | Total Chain Length (m) | Chain Size (mm) | Rope/ Wire Length (m) | Rope/ Wire Diameter (mm) | Ancillaries | Anchor Type | Anchor Sizing (Te) |
|---|---|---|---|---|---|---|---|---|---|
| **Catenary D** | Chain | 3 | 750 | 152/114 | - | - | - | DEA | 30 |
| **Catenary E** | Chain | 3 | 750 | 152 | - | - | - | Driven Pile | 41 |
| **Catenary F** | Chain, Steel Wire | 3 | 650 | 152 | 100 | 130 | - | DEA | 25 |

| Configuration Name | Line Type | No. of Lines | Total Chain Length (m) | Chain Size (mm) | Rope/ Wire Length (m) | Rope/ Wire Diameter (mm) | Ancillaries | Anchor Type | Anchor Sizing (Te) |
|---|---|---|---|---|---|---|---|---|---|
| **Catenary G** | Chain, Synthetic Rope | 3 | 650 | 112 | 100 | 195 | - | DEA | 25 |
| **Mixed Buoyant B** | Chain, Synthetic Rope | 3 | 400 | 152/ 114 | 150 | 230 | Buoyancy Modules | DEA | 15 |
| **Taut B** | Chain, Synthetic Rope | 3 | 50 | 152 | 350 | 200 | - | Driven Pile | 55 |
| **LRD A** | Chain | 3 | 750 | 81 | - | - | LRD | DEA | 20 |
| **LRD B** | Chain | 3 | 350 | 152 | - | - | LRD | DEA | 20 |
| **LRD C** | Chain, Synthetic Rope | 3 | 250 | 81 | 100 | 195 | LRD | DEA | 20 |
| **LRD D** | Synthetic Rope | 3 | - | - | 120 | 200 | LRD | DEA | 25 |
| **Shared Anchor** | Chain | 3 | 850 | 152/ 114 | - | - | - | Suction Bucket | 88 |

# 6 CARBON EMISSIONS ASSESSMENT

This section presents results of the carbon emission assessment completed within the LCA analyses. Results are presented for mooring components, processes and systems to identify the highest contributing factors to carbon emissions. An analysis of base case and alternative configurations provide a system wide representation of all components involved in the study and present carbon reduction opportunities. Comparison of alternative mooring configurations against the base case configurations presented in Section 5, highlight the potential carbon reductions that can be achieved through component changes. The following carbon emission outputs related to each mooring configuration are presented in this section:

- Transportation review
- Anchor Review
- Base case Catenary A configuration breakdown
- Base case configuration analysis
- Alternative configuration analysis

## 6.1 Transportation

Transportation emissions of the different mooring configuration materials have been separated from the final results. This allows the final results to be interpreted solely on the material selection, manufacturing methods and installation types of each configuration. It also allows the values to be applied to specific case studies depending on the reader's choice. Transportation scenarios from one port situated in Asia and one port in Europe are used to highlight the impact of material origin.

Steel is the most abundant material used across the different mooring configurations, due to the necessity of chains and anchors. A 2022 report issued by DNV indicates that the European market will struggle to supply the volume of steel required to satisfy the 1GW per annum capacity demand of floating substructure manufacturers [29]. It is likely that this impact will be experienced across chain and anchor fabrication as well due to the high volumes required to accompany these substructures.

The ports included in this review are Rotterdam (Netherlands) and Guangzhou (China). The UK reference port for import is assumed as Southampton. The aim of this comparison is to review the additional carbon emissions produced when steel is transported from Asia compared to Europe with the two case studies included being, the Netherlands and China. Approximately 375 tonnes of imported steel is required for the fabrication of a single mooring line and anchor. This value is consistent with the "Catenary A" configuration described in Section 5.1.6. The transportation vessel is assumed to be a medium size bulk carrier commonly used for construction materials such as steel. The distances associated with each port are shown in Table 24.

Table 24: Transportation Emissions

| Port Route | Country | Sea Route Distance |
|---|---|---|
| Rotterdam - Southampton | Netherlands - UK | 487km |
| Guangzhou – Southampton | China - UK | 19,031km |

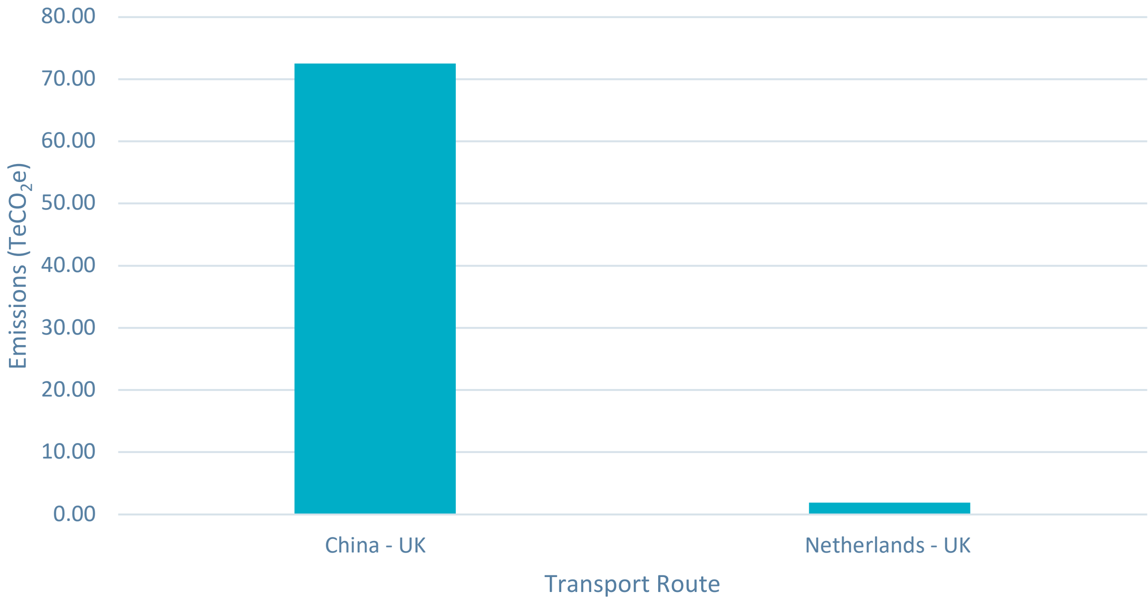


Figure 25: Representative Transportation Carbon Emissions

The total emissions calculated for each transportation route carrying 375 tonnes of steel is shown in Figure 25. The results show that emissions to ship steel to the UK from China are approximately 40 times greater than from the Netherlands. Transport distance is the predominant factor, however it is important to note that emissions would increase considerably for larger material quantities.

## 6.2 Anchor Type Review

The aim of the anchor type review is to show the carbon emission impact when using different anchor types in a range of seabed types. Anchor UHC is impacted by the size of the anchor and the seabed conditions, and therefore the anchor size must vary to achieve the same UHC for different seabed conditions.

The three seabed types and the mass of each anchor selected are defined using the sizing tool included in the ABS report “Development of mooring-anchor program in public domain for coupling with floater program for FOWTs” [5]. The seabed types included in the ABS report range from softer to harder sediments; soft clay/mud, medium clay and sand/hard clay. The Celtic Sea sites, detailed in Section 1.1, include a table on the different site characteristics that show a range of sediments. The ABS defined seabed types are not a direct match to the Celtic Sea sites, but do offer a representative range for the analysis.

Suction buckets and driven piles were reviewed only for compatible seabed types whereas DEAs, which are rarely used for harder conditions, have been applied to all seabed types. This is due to new novel technologies and the development DEA types which are specifically designed to penetrate harder sediments. These anchor types are further explored in Section 7.1.2, but as these new or novel designs have the potential to be deployed in harder conditions, it was deemed worthy to include these in the study.

Gravity anchors are not included in the analysis as they are yet to deployed for any FOW project. VLAs haven’t been included in the analysis, however they have comparable properties to DEAs and the results can be treated as such.

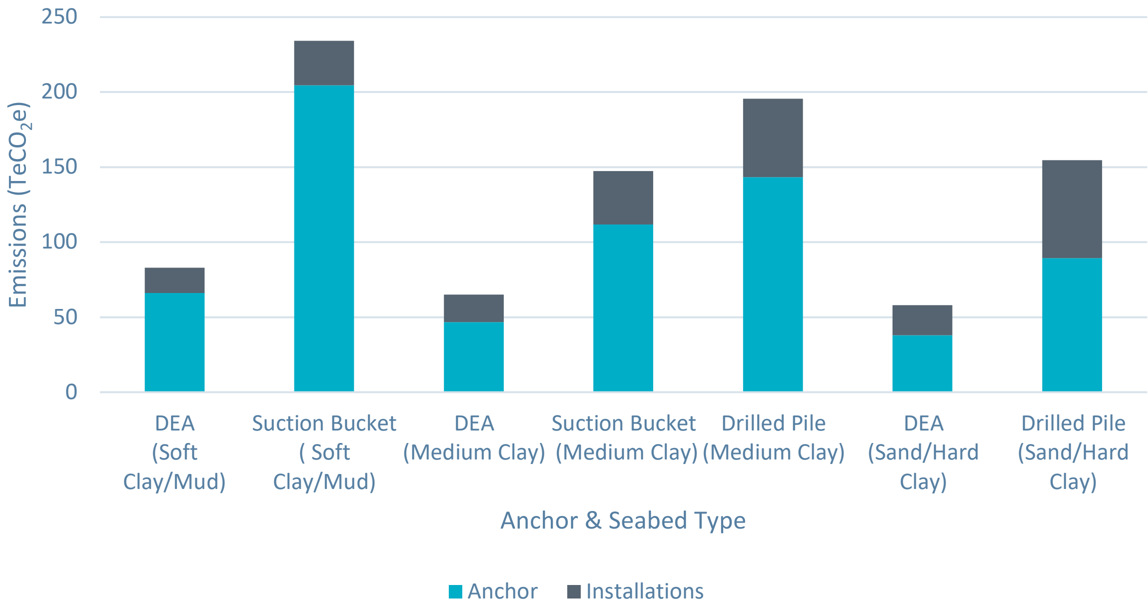


Figure 26: Emissions considering Anchor Types and Seabed Conditions (12,000kN UHC)

DEA anchors have the lowest total carbon emissions across all seabed types as shown in Figure 26. This is due to the lower mass and shorter installation times compared to other anchors. Suction buckets and driven piles both require additional steel and have more complex installation processes. Suction buckets produce less carbon emissions than driven piles in a medium clay seabed due to their smaller mass and simplified installation process.

Driven piles are preferred for vertical loading in a sand/hard clay seabed. Carbon emissions are lower for driven pile anchors when installed in the harder seabed due to the design mass requirements being lower compared to softer seabed types to achieve the necessary UHC.

The results show that DEA anchors offer significantly lower emissions compared to other anchor types, although all anchor types will be required to suit the seabed conditions of future projects. The results demonstrate that different anchors can reduce carbon emissions when deployed in the most compatible seabed.

The carbon emissions identified for each anchor and seabed type offer a good insight on the carbon emissions for anchor solutions on the market. However, it is important to consider these anchor types and associated carbon emissions within the context of the entire mooring configuration. The following sections explore a variety of mooring configurations using different anchor types, where the carbon impact of the anchor within the mooring configuration can be observed.

## 6.3 Base Case Catenary A Configuration Breakdown

A breakdown of the carbon emissions associated with the main components and life cycle processes of the default base case mooring configuration, Catenary A (Setup reference Table 9), is shown in Figure 27. This breakdown is presented to highlight the components and processes which contribute most to the carbon emissions in a typical steel chain catenary mooring configuration. The sections that follow investigate how different configurations can reduce carbon emissions with emphasis on steel chain material reduction, as this was identified as the single greatest contributor (88.1%) to carbon emissions.

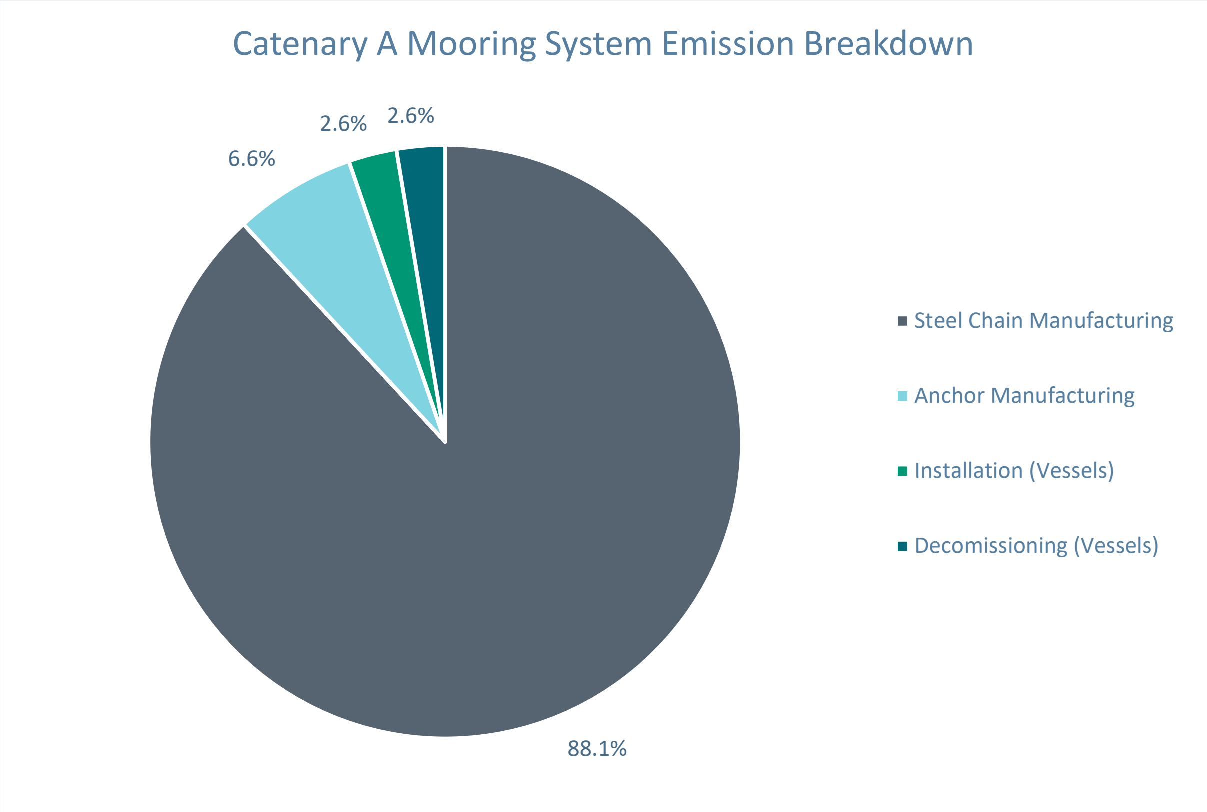


Figure 27: Catenary A Mooring Configuration Emission Breakdown

## 6.4 Base Case Mooring Configurations

The base case mooring configuration comparison aims to highlight the carbon emissions for each typical mooring configuration that could be used in the floating wind industry. The carbon emission impact calculated for each of the base case mooring configurations is presented in Figure 28.

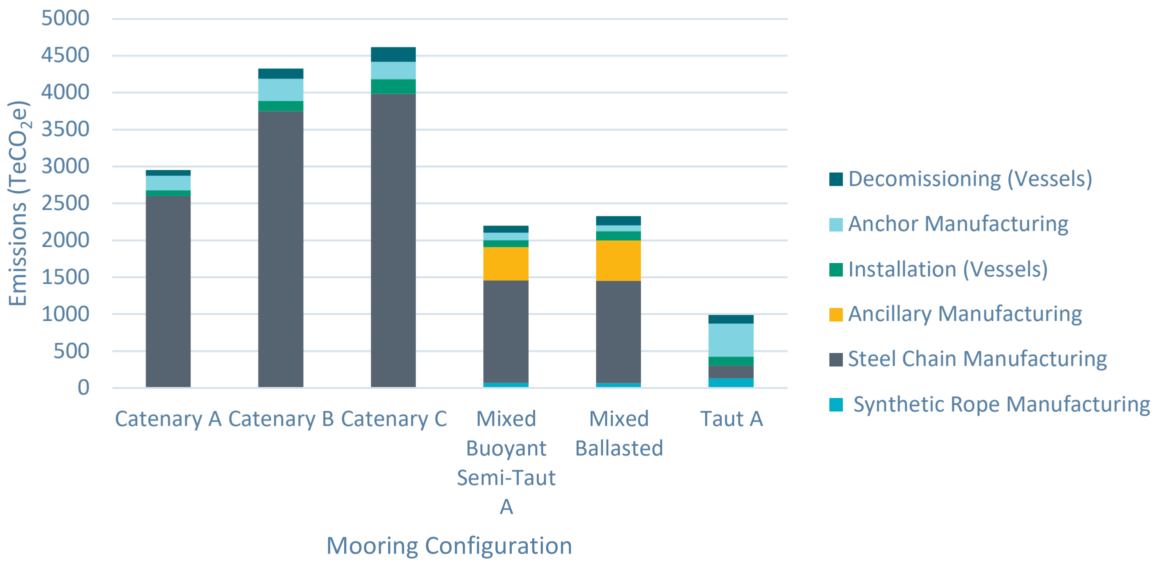


Figure 28: Base Case Mooring Configuration Carbon Emissions

Steel chain is shown to be the highest contributor to carbon emissions within Catenary A (Setup reference Table 9). This is due to the significant amount of embodied carbon associated with manufacture and transport, in conjunction with the high quantity of chain length required to produce the mooring configuration geometry.

Additional lines in Catenary B (Setup reference Table 10) and Catenary C (Setup reference Table 10) result in an increase in emissions. From Figure 28 it is clear the carbon emissions do not increase at the same rate as the quantity of lines increase. This is due to the reduced chain diameter and anchor holding capacity required as the number of mooring lines increase. The additional lines also result in increased installation time, and therefore, increased installation vessel carbon emissions.

The results show that all non-catenary configurations have lower emissions than the catenary configurations. This is due to the reduction in steel chain and line length. The non-catenary configurations include a section of synthetic rope to partially replace the steel chain in the mooring line, and this significantly reduces the material mass in the mooring configuration. The manufacturing process for synthetic rope has similar levels of embodied carbon to the manufacturing process for steel chain, however, the reduced material mass required for the equivalent length of synthetic rope results in significantly less carbon emissions produced for the mooring configuration.

The mixed ballasted configuration (Setup reference Table 11) has additional ancillary related carbon emissions due to the clump weights added to the mooring configuration. The embodied carbon of steel manufacture for the clump weights is the main contributor to the clump weight related carbon emissions. Overall, it has lower carbon emissions than the catenary configurations because the carbon emission savings made by significantly reducing the quantity of steel chain is far greater than the carbon emissions contributed by the clump weights. The Mixed Buoyant A configuration (Setup reference Table 12) has additional ancillary related carbon emissions due to the buoyancy units added to the mooring configuration. The embodied carbon of manufacturing the low-density polymer material for the buoyancy units is the main contributor to the buoyancy unit related carbon emissions. Overall, it has lower carbon emissions than the catenary configurations because the carbon emission savings made by significantly reducing the quantity of steel chain is far greater than the carbon emissions contributed by the buoyancy units. The Taut mooring configuration (Setup reference Table

13) produces the lowest carbon emissions across all mooring configurations as the mooring line is made predominantly from synthetic rope, with a short 50 metre section of steel chain. A suction bucket anchor is incorporated to withstand vertical loading in a taut configuration, which increases carbon emissions for steel manufacture due to the increased anchor size. However, the total emissions in the taut mooring configuration are minimised due to the significantly reduced dependency in steel chain. This analysis shows the significant potential carbon emission savings that a taut configuration can achieve, however, this configuration is yet to be proven at commercial scale and will likely require additional ancillary equipment such as LRDs. .

The following section explores the potential carbon emission reduction opportunities of using alternative mooring configurations when compared to the base case configurations.

## 6.5 Alternative Mooring Configurations

### 6.5.1 Alternative Catenary Configurations

The following alternative configurations highlight the potential carbon emission savings that can be achieved from altering the catenary configurations. Table 25 provides a summary of the mooring configurations used in the alternative catenary analysis, and the results are shown in Figure 29.

Table 25: Alternative Catenary Configurations

| Configuration Name | Line Type |
|---|---|
| **Catenary A** | Basic 3 line steel chain catenary base case |
| **Catenary D** | Catenary with ground chain of a reduced diameter |
| **Shared Anchor** | Catenary with shared anchors and reduced ground chain diameter |
| **Catenary E** | Catenary A with driven pile anchors instead of DEAs |
| **LRD D** | Fully optimised configuration with LRDs, suitable for typical catenary scenario |

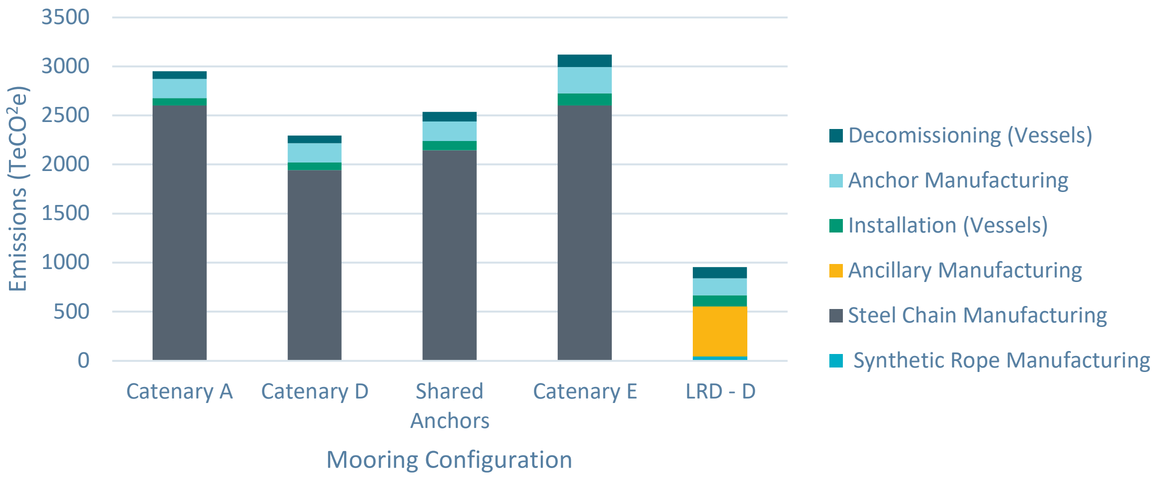


Figure 29: Alternative Catenary Mooring Configuration Carbon Emissions Comparison

### Catenary D

Catenary D (Setup reference Table 15) investigates the impact of reducing ground chain diameter in the mooring configuration. Catenary D results in a 22% reduction in carbon emissions compared to Catenary A (Setup reference Table 9), which is a considerable drop for such a simple adaption. This demonstrates the importance of streamlining the mooring design and avoiding over-engineering where possible.

### Shared Anchor

Shared anchoring (Setup reference Table 19) introduces a more complex adaption to default base case Catenary A (Setup reference Table 9). As stated in Section 5.2.5 there are substantial design changes required for a shared anchor configuration, including increased mooring line length and anchor UHC. Despite these added complexities, a 14% reduction in $TeCO_2e$ emissions is presented in the results. This carbon emission reduction in the overall configuration is due to the reduced quantity of anchors, but is limited due to the increased dependency on steel chain lengths and anchor size required to withstand more onerous loads. For commercial scale windfarms, increasing the number of FOWTs with shared anchors can further reduce the total number of anchors required within a wind farm by up to 67%, therefore offering additional reductions to carbon emissions across wind farm mooring configurations [28].

### Catenary E

Catenary E (Setup reference Table 20) results in more carbon emissions than default base case Catenary A (Setup reference Table 9) due to the use of driven pile anchors instead of DEAs. The change from DEAs to driven pile anchors has increased the carbon emissions across anchor manufacture, mooring system installation and decommissioning. However, by using the driven pile anchor, the overall mooring configuration carbon emissions only increase by approximately 6%.

### LRD-D

LRD-D (Setup reference Table 18) shows the maximum potential savings in carbon emissions (68%) through the application of an LRD device compared to a traditional steel chain catenary configuration. The results show that including an LRD offers significant reductions in carbon emissions due to the large reduction in steel chain. The reduction in anchor size required also reduces carbon emissions. The synthetic rope contributes the lowest proportion of mooring configuration emissions, contributing only 9% overall. While LRDs are seen to significantly reduce carbon emissions, the LRD component contribution varies by design and size. A conservative estimate was made for the LRD device carbon emissions at 500Te$CO_2$e, which is added to the total carbon emissions through the ancillary metric. LRD technologies are considered to be novel and are currently not available for commercial FOW deployment, however these results illustrate the potential for carbon reduction from these configurations.

### 6.5.2 Alternative Catenary Configurations Using Synthetic Rope and Steel Wire Sections

A comparison of Catenary A, with alternative catenary configurations using sections of steel wire and synthetic rope are shown below. Table 26 provides a summary of the mooring configurations used in the analysis, and the results are shown in Figure 30.

Table 26: Alternative Catenary Configurations using Synthetic Rope and Steel Wire Sections

| Configuration Name | Line Type |
| --- | --- |
| **Catenary A** | Basic 3 line steel chain catenary base case |
| **Catenary F** | Catenary with steel wire insert |
| **Catenary G** | Catenary with synthetic rope insert |

Catenary F (Setup reference Table 16) and Catenary G (Setup reference Table 17) result in lower emissions compared to Catenary A (Setup reference Table 9) as they incorporate less steel chain. Complete removal of steel chain in a catenary configuration is so far unproven, the opportunity for reduction in carbon emissions observed in hybrid mooring configuration such as Catenary F and Catenary G is observed in Figure 30.

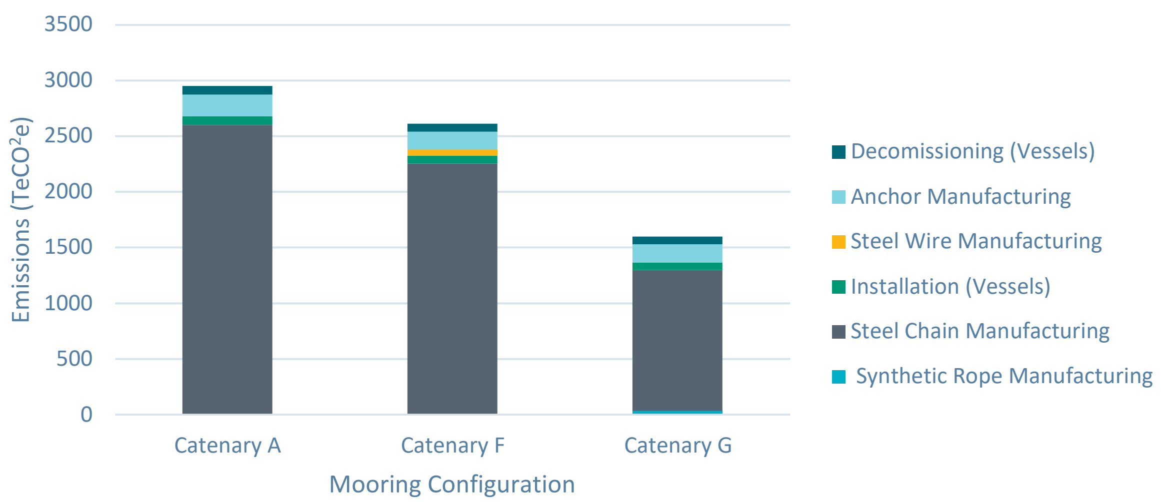


Figure 30: Hybrid Catenary Carbon Emissions Comparisons

The base case carbon emissions are reduced by 12% for the steel wire hybrid configuration (Catenary F), and are reduced by 46% for the synthetic rope hybrid configuration (Catenary G). In Catenary G the low stiffness of the synthetic rope insert reduces load in the mooring line and allows for a reduction in the chain diameter leading to lower carbon emissions in comparison to Catenary F, which is negatively impacted by the steel wire insert and larger chain diameter. This is the main contributor to the reduction in emissions from Catenary F to Catenary G. The emissions from the manufacturing of synthetic rope in Catenary G total 35Te$CO_2$e, approximately half of Catenary F's steel wire content of 69Te$CO_2$e.

### 6.5.3 Alternative Buoyant Semi-Taut Configuration

Table 27 provides a summary of the mooring configurations used in the alternative buoyant semi-taut configuration analysis, and the results are shown in Figure 31.

Table 27: Alternative Buoyant Semi-Taut Configurations

| Configuration Name | Line Type |
|---|---|
| **Mixed Buoyant Semi-Taut A** | Mixed buoyant semi-taut base case |
| **Mixed Buoyant Semi-Taut B** | Mixed buoyant semi-taut with ground chain of a reduced diameter |

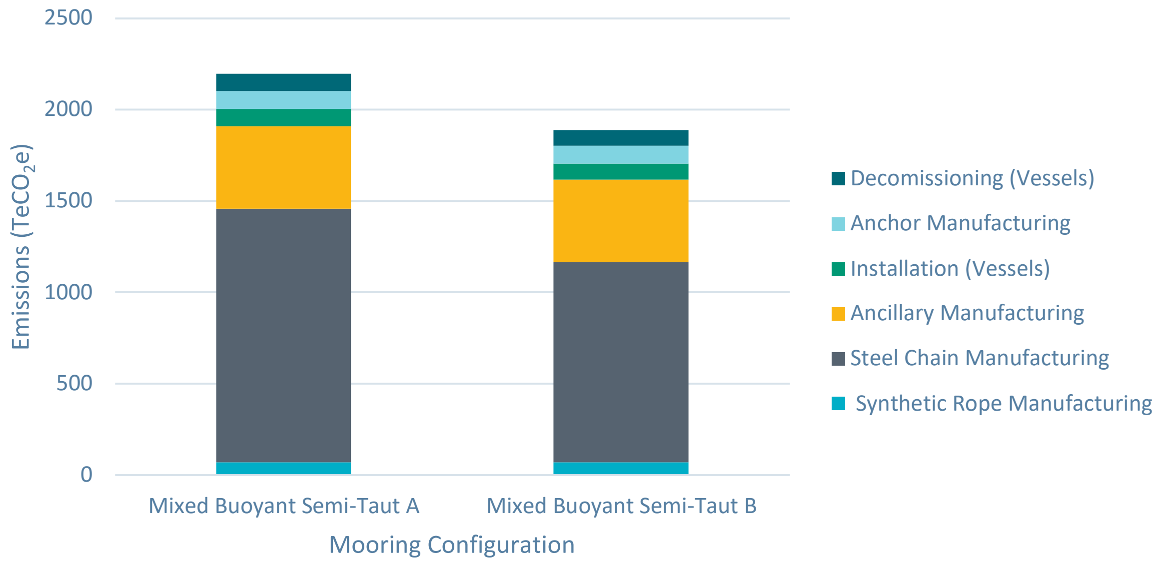


Figure 31: Alternative Mixed Buoyant Semi-Taut Carbon Emissions Comparison

A smaller ground chain diameter for Buoyant Semi-taut B (Setup reference Table 22) offers a small reduction in carbon emissions (14%) compared to Buoyant Semi-taut A (Setup reference Table 12). This is a smaller reduction in carbon emissions than observed in the catenary configuration with reduced ground chain diameter (22%), as there is less chain length available to optimise. The buoyant semi-taut configuration already considers alternative materials and components, and therefore there is limited opportunity for further optimisation without switching to a taut configuration.

### 6.5.4 Alternative Taut Configuration

For this comparison, each anchor type has been applied to the most suitable seabed which results in the lowest installation emissions. The anchor size and variation compared to seabed is detailed in Section 6.20. From this section it is known that suction buckets are best suited to medium clay, while driven piles are better suited to sand/hard clay in terms of installation carbon emissions. Table 28 provides a summary of the mooring configurations used in the alternative taut configuration analysis, and the results are shown in Figure 29.

Table 28: Taut Configurations

| Configuration Name | Line Type |
|---|---|
| **Taut A** | Base case taut configuration using suction buckets in medium clay seabed |
| **Taut B** | Taut configuration using driven pile anchors in sand/hard clay seabed |

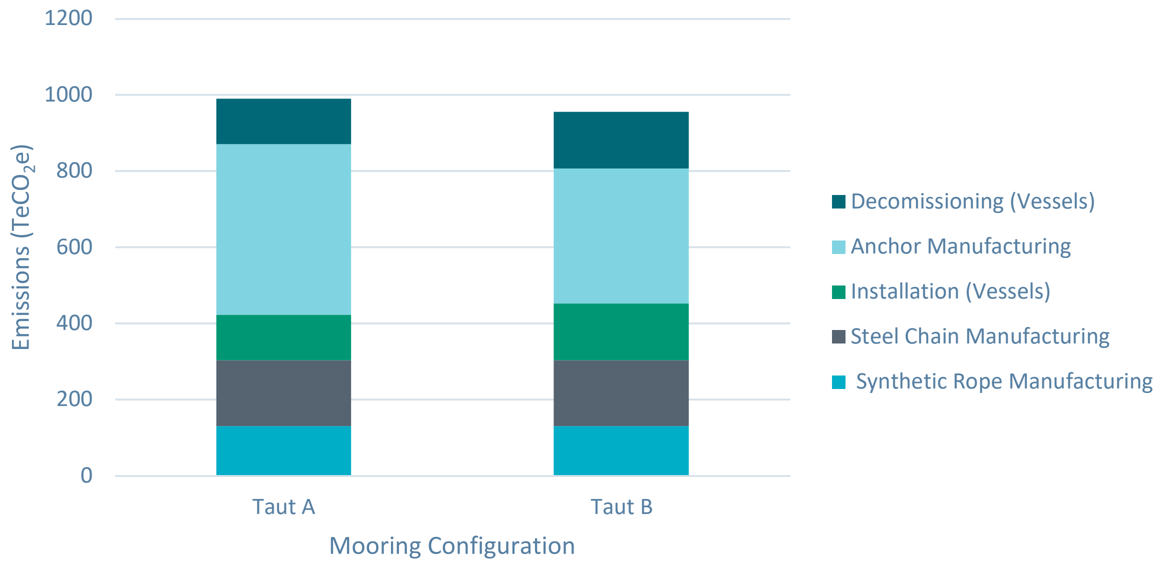


Figure 32: Alternative Taut Configuration Carbon Emissions Comparison

The taut configurations have the least carbon emissions of all the mooring configurations included in this study. It was stated in Section 6.3 that this is due to the significant reduction in steel chain which is the highest contributor in most mooring configurations analysed.

In this configuration, synthetic rope was used to replace sections of steel chain, meaning the resultant anchor related emissions have an increased impact on the overall carbon emissions of the mooring configuration. An anchor can contribute to over 40% of the carbon emissions for a taut configuration, whereas in a catenary it can be as low as 10%.

The emissions generated from Taut A (Setup reference Table 13) are greater than Taut B (Setup reference Table 21) due to the higher volume of steel required for the suction bucket. However, the Taut B configuration has greater installation and decommissioning carbon emissions due to the additional time and complexity involved with driven pile installation compared to suction buckets, which partly offsets the carbon emission saving in the reduced anchor material required. The Taut B configuration produces 4% less carbon emissions compared to the Taut A configuration.

These results highlight the importance of anchor optimisation within the taut mooring configurations.

### 6.5.5 Alternative LRD Configurations

The impact of an LRD device on the mooring configurations in this study have been formed through industry engagement and adapted to allow for a conservative estimate regarding the emissions associated with the construction and fabrication of an exemplary LRD device. The carbon reduction opportunities that could be realised with the use of an LRD are shown in Figure 33, and a summary of these alternative LRD mooring configurations is provided in Table 29.

Table 29: Alternative LRD Configurations

| Configuration Name | Line Type |
|---|---|
| **Catenary A** | Basic 3 line steel chain catenary base case |
| **LRD - A** | Catenary A with an LRD installed to reduce the steel chain diameter |
| **LRD - B** | Catenary A with an LRD installed to reduce the steel chain length |
| **LRD - C** | Catenary G with an LRD installed to reduce the steel chain length |
| **LRD - D** | Taut configuration with LRD added which is compatible with a catenary environment |

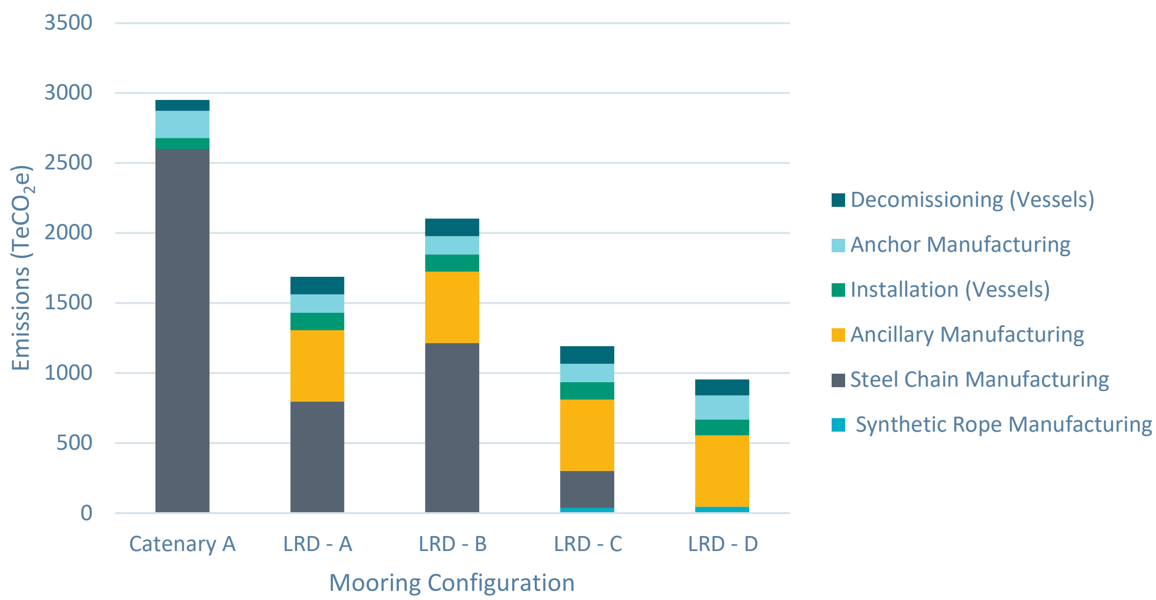


Figure 33: Alternative Catenary Configuration with LRD Optimisation Carbon Emissions Comparison

All LRD configurations offer a reduction in carbon emissions with the greatest reduction being LRD – D, which was reviewed in Section 6.5.1, as it is designed to replace a catenary configuration with a taut configuration using an LRD.

LRD – C (Setup reference Table 18) achieves a 60% reduction in $TeCO_2e$ through reducing the steel chain length by 500 metres and adding 100 metres of synthetic rope to the mooring configuration.

In LRD – B (Setup reference Table 18) the LRD device allows the steel chain length to be reduced by 400 metres resulting in a 29% decrease in carbon emissions.

LRD – A (Setup reference Table 18) accomplishes a greater reduction in $TeCO_2e$ compared to LRD - B because the LRD device allows the reduction in steel chain diameter rather than length reducing emissions by 43%. This emphasises the positive impact of lower steel chain diameter on carbon emissions.

The additional emissions generated from the LRD are still notably less than the steel chain emissions associated with the Catenary A configuration, therefore, applying the LRD device still results in considerable improvements to the total emissions generated.

## 6.6 Key Findings

The results presented in this section demonstrate that steel is the largest contributor to carbon emissions across the different mooring configurations. This is mainly due to the embodied carbon associated with steel production in addition to the considerable masses required for each configuration.

This section investigated several minor and major adaptions to mooring configurations, and their overall impact on carbon emissions when compared to a steel chain catenary base case mooring configuration. The key findings from the analyses are summarised below:

- Shipping mooring components from Asia to the UK can produce approximately 40 times greater emissions per journey in comparison to export from a European port.
- DEAs have the least carbon emissions of the anchor types as they use less steel and are simpler to install. However, other anchor types can enable greater reductions in total carbon emissions when analysed at a system level.
- Despite requiring less installation vessel time and capacity compared to anchors deployed in harder seabed conditions, anchors deployed in softer seabed conditions increase total carbon emissions as they require greater material mass to achieve the necessary UHC.
- A reduced ground chain diameter can result in lower carbon emissions of between 14% to 22%. The scale of this reduction is directly influenced by the amount of steel ground chain that remains within each configuration.
- Semi-taut or taut configurations can reduce carbon emissions by 26% and 66% respectively, providing the FOWT, seabed and operational environment are suitable for these configurations.
- Replacing 100 meters of steel chain with synthetic rope or steel wire chain can reduce carbon emissions by 46% and 12% respectively.

- LRDs can introduce various improvements such as a reduction in steel chain diameter, mooring line length, and potentially increase the suitability of taut or semi-taut configurations over conventional catenary configurations.
- LRDs can reduce carbon emissions between 29% and 68%, although these devices are still to be deployed at full scale.

# 7 CARBON REDUCTION OPPORTUNITIES

Offshore wind is expected to play a key role in the decarbonisation of our energy supply. However, despite their contribution to zero emission energy, offshore wind farms hold an embodied carbon cost, associated with the materials used for construction, transportation and installation of components at site, and through the decommissioning stage at the end of life.

Design and process modification across the full life cycle of the mooring system can be a key enabler of decarbonisation in FOW projects. The results from the mooring system carbon emissions LCA presented in this study have highlighted where potential carbon emission reductions can be achieved. Further opportunities for carbon emission reduction and analysis are also identified.

## 7.1 Design Modifications

It has already been demonstrated across the range of base case and alternative mooring configurations presented that there is significant opportunity for carbon emission reduction through design modifications. The key opportunities to reduce carbon emissions in mooring system design are presented in this section.

### 7.1.1 Mooring Line Design Development Opportunities

**Steel Chain Size Optimisation**

It has been demonstrated throughout the carbon emission assessment that the use of large diameter steel chain has the most carbon emissions of the mooring line materials used. Floating offshore wind turbines are anticipated to increase in capacity and size, and so it is predicted that steel chain may need to be increased in size too. Mooring designers must explore opportunities to reduce steel chain size where possible, such as in the ground chain section of the mooring line where there is less load acting on the chain. Reducing the ground chain length and diameter are both ways to reduce carbon emissions in the mooring configuration, however this potential design optimisation must be backed up by detailed analysis. Mooring configurations with more than three lines also present the opportunity to reduce chain diameter, as the load is distributed over a greater number of lines. Reduced chain size will also present more opportunity for the manufacturing industry in the UK to supply Celtic Sea FOW projects.

**Synthetic Rope Usage**

The results of the carbon emissions LCA have shown that the use of synthetic rope as an alternative to steel chain gives the opportunity to maximise carbon reduction potential. However, the use of synthetic rope typically requires additional ancillary equipment added to the mooring configuration, such as buoyancy, ballast or LRDs. Synthetic ropes are also less proven for long-term mooring application than steel chain, and therefore, design and technology development is needed to bring synthetic ropes to the commercial FOW market and to maximise carbon reduction potential.

### 7.1.2 Anchor Design Development Opportunities

It has been found that carbon emissions vary significantly across the different anchor types deployed in a variety of seabed conditions. With the challenging range of seabed conditions present in the Celtic Sea, it is crucial for the development and refinement of anchor solutions to be explored to reduce carbon emissions. With material manufacturing and fabrication of anchors being the greatest contributor to anchor carbon emissions in the life cycle, the main opportunity to reduce carbon emissions is by developing anchor solutions that enable reduction in size. DEAs are found to have less carbon emissions than suction buckets and driven piles with the equivalent UHC, however it is known that they are not suitable for vertical or multi-directional loading. Novel anchor solutions such as VLAs are designed and installed similarly to DEAs but are able to withstand vertical load. VLAs present the opportunity to reduce anchor manufacture and fabrication carbon emissions, compared to conventional anchor solutions capable of withstanding vertical load, such as the suction bucket or driven pile. For hard seabed conditions that require driven anchors, there are also novel anchor solutions, such as torpedo anchors and micro-piles, with the opportunity to reduce anchor mass and, therefore, carbon emissions, compared to a conventional driven pile solution. New DEA designs are also being produced that are suitable for harder seabed types as they have been adapted to penetrate harder soils.

### 7.1.3 Shared Anchor Opportunities

It has been demonstrated that shared anchor solutions can reduce carbon emissions compared to a typical catenary configuration, although current solutions are conservative in design. Therefore, further design innovations could be realised for shared anchors.

Using shared anchors in this way reduces the number of total anchors required and can also potentially reduce the required anchor size in mooring systems where anchor loading is more evenly distributed from mooring lines in multiple directions.

It has been discussed that taut and semi-taut mooring configurations have significant carbon emission savings compared to conventional catenary configurations, however carbon emissions could be reduced further by deploying a shared anchor solution for taut and semi-taut mooring configurations. This will require further development and testing of shared anchors to ensure they can withstand more complex multi-directional loads.

### 7.1.4 Ancillary Design Development Opportunities

#### Buoyancy modules

It was found that buoyancy modules can support decarbonisation of other mooring components, such as their application in a semi-taut mooring system, which can reduce the length of steel chain required and support the integration of synthetic rope.

#### Ballast Modules (Clump Weights)

Clump weights are a proven technology used in the O&G industry, and their design and manufacture processes are relatively mature. Clump weights can enable carbon reduction by tuning mooring configurations, which in turn can reduce other material dependencies such as steel chain or anchors.

#### Load Reduction Devices

Load reduction devices can enable significant decarbonisation of other mooring configuration components. LRDs allow for optimisation of line and anchor sizes by reducing the loads in mooring system. Load reductions can influence the design of the floating substructures, which can enable a reduction in their overall mass. This applies to both steel and concrete substructures where a reduction in substructure mass can lead to a significant reduction in carbon emissions. Further refinement and commercialisation across the various LRD designs currently under development could help realise carbon reductions in future FOW projects.

#### 7.1.5 Standardisation

The design of FOW mooring configurations has generally been conducted on a case-by-case basis to date with little consideration for the serial production required for commercial FOW. Bespoke mooring components, such as uniquely sized steel chain and anchors, can require bespoke manufacturing equipment and lead to complexities in installation. Standardisation in the design of components and manufacturing processes can help reduce lead times and demand for bespoke equipment, which can reduce overall carbon emissions.

### 7.2 Process Modifications

It is possible to reduce carbon emissions by retaining conventional design but through alterations to materials, manufacturing processes, installation methods, transport options and production locations. This section explores these key opportunities to reduce carbon emissions through process modification.

#### 7.2.1 Cleaner Materials/Manufacturing

One of the largest areas of carbon emissions is from raw material production, one way of reducing this is through the use of recycled or eco materials.

**Recycled and Green Steel**

Steel is an extremely versatile material that is essentially 100% recyclable, the UK already has a strong scrap steel infrastructure capable of repurposing material at a number of steel manufacturing sites. According to Make UK [30], UK steel sites using scrap material and electric arc furnaces (EAF) produce 80% less emissions than equivalent ore-based sites. Research shows UK steel production sites are less carbon-intensive at producing ore-based and scrap-based steel compared to the global average [30], therefore, in most cases imports will result in higher carbon emissions. Additionally, increased imports of finished steel products will also boost transport-related emissions as seen in section 6.1, which highlighted that shipping one tonne of product from a port in China is estimated to result in 40 times the emissions of an equivalent load from the Netherlands. The precise net impact on transport related emissions due to imports compared to domestically produced steel is more complex and must take account of the shipping of raw materials to make the steel and the density of products. However, given that most ore-based producers in the world import raw materials and significant quantities of steel in the UK are produced from domestically produced scrap it is evident that transporting increasing volumes of finished steel products to the UK would lead to more emissions than transporting raw materials and producing steel products in the UK.

Another production change that can create a large impact is green steel. As renewable infrastructure scales up, so does the potential for green steel production [31]. Green steel requires two things, a source of clean electricity and a green heat source. By using excess electricity and hydrogen produced by electrolysis from renewable sources, it’s possible to create a net-zero steel. One of the biggest steel plants in the UK is based on the Celtic sea coast, Tata Steel Port Talbot, which is headlined as being a key port for floating wind and has recently been in the news regarding links to offshore developer partnerships [32] The steel sites proximity to large amounts of offshore wind could open opportunities for this site to be transitioned to clean electricity.

**Bio Synthetics**

The use of HMPE lines are popular on existing demo projects (Table 2), where it has been used in combination with chain catenary configurations. Bio synthetics offer the same material characteristics but with a lower carbon footprint. Figure 34: Synthetic Rope Figure 34 produced by company DSM shows a comparison between synthetic line products against its bio-based Dyneema product.

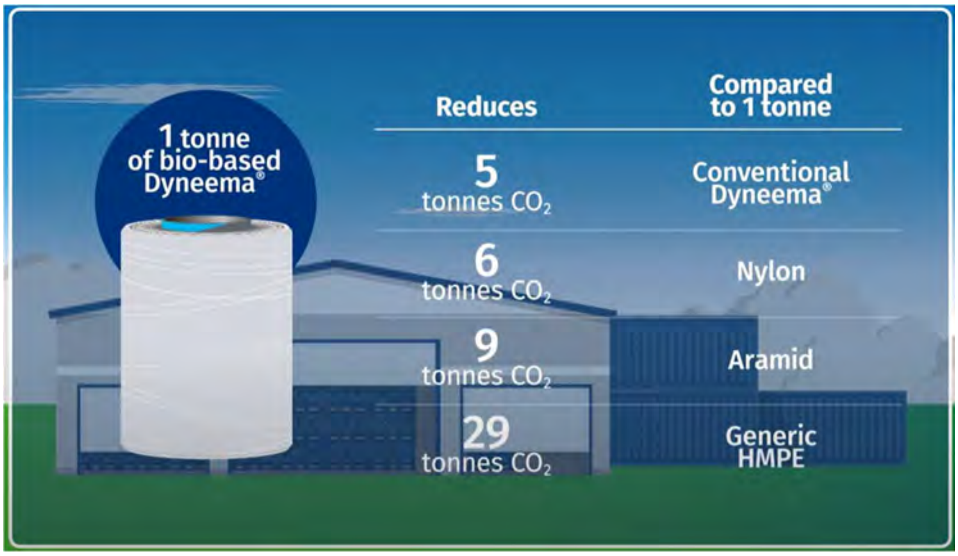


Figure 34: Synthetic Rope [33]

Bio-based Dyneema fibre claims to have a carbon footprint that is 90% lower than generic HMPE fibres whilst maintaining the exact same performance and specifications as conventional Dyneema [33]. It achieves this through use of by-product from the timber and pulp industries in the ethylene production process. Products like bio-Dyneema show it is possible to adapt the manufacturing process and raw material inputs to replicate the same products with the same performance but with a lower carbon impact. Dyneema lines have very low stretch characteristics and may not be suitable for different designs. However, the capability to reduce emissions through production of bio-based fibres is promising and has the opportunity to be replicated across other line types.

**Recycled/Reused Synthetics**

The processes to recycle or reuse synthetic rope is not particularly well known in the offshore industry, current end of life treatment for synthetic rope is generally assumed to be landfill. There are two methods which look to decrease the carbon emissions related to synthetic rope. The first method aims to repair the synthetic rope to allow it to be reused in the industry. Method two involves breaking down the synthetic rope into granulate and either using it to fabricate new mooring lines or it can be applied to make other products.

### 7.2.2 Installation

To deploy the number of anchors and mooring lines expected for FOW arrays, large AHVs with low availability and expensive day rates likely won't be feasible for installation of commercial FOW. Reduction in installation process emissions will likely come from two main areas. As discussed in section 4.3.4, installation tools will be key to making smaller vessels more capable. Products such as tensioners can reduce required load by up to 60% and can make the need for bollard pull or winch capacity in excess of the installation load obsolete. Quick connector options also claim to drastically lower the time and skill required to attach dynamic cables and mooring lines.

Secondly, alternative fuels for vessels, there is already a number of different vessels that have either been retrofitted or designed with propulsion systems that reduce carbon impact. The focus of developers on clean vessels for the renewables industry has increased with notable orders placed for

SOVs and crew transfer vessels (CTVs) in the O&M space. Possible fuel replacement options are listed in Table 30.

Table 30: Alternative Fuels [34]

| Carbon Fuels | Carbon Neutral | Zero Carbon |
|---|---|---|
| Liquified Natural Gas (LNG) | Biofuels/Biomethane | Hydrogen |
| Liquified Petroleum Gas (LPG) | Synthetic Methane | Ammonia |
| Methanol/Ethanol | - | - |
| Battery Hybrids | - | - |

Orsted recently announced its procurement of the worlds first green fuel powered SOV [35] The known transit times and base port will see O&M vessels become first adopters of green vessel innovation but as infrastructure and technology progresses this will likely spread towards installation and construction craft.

## 7.3 Limitations and Future Work

This study included a number of limitations due to a lack of available information. The main omissions being O&M and decommissioning. The reasons behind omitting these areas and the potential future topics which should be developed or researched further are discussed in this section.

**O&M**

O&M emissions associated with mooring components are dependent on several factors. The information required to distinguish the testing and monitoring of the different mooring systems would be difficult to calculate due to the weather windows, along with the additional literature review needed to accurately calculate each stage of the processes. Therefore, O&M emissions have been excluded from this study.

**Decommissioning**

Decommissioning is an important aspect of the LCA which is why the emissions associated with disconnecting and return to port is assumed and included. However, the potential landfill or recycling of the different components is not due to the lack of available information on recycling.

Steel chain is a clear example, recycling of chain is possible but often disregarded as it is an energy intensive and costly process. Steel chain may incorporate recycled steel, however, it is unlikely to involve recycled chain. This area needs further attention due to the volume of steel chain required to meet future floating wind demand.

Synthetic rope is generally expected to be landfilled, but there are some companies looking into the possibilities of reusing and recycling the material. As stated in Section 7.2.1, the potential to decrease the carbon emissions associated with synthetic rope is available, however this is still a new concept meaning and further work is needed for it to mature.

Overall, the decommissioning of a FOW farm is yet to occur which leaves little information regarding the specific process. That said, it is important consider the challenges and possibilities to understand which methodologies are the best way forward. This is why the end of life part of the decommissioning has been omitted from the calculations in this study, but the topic surrounding the recycling of these materials at their end of life has been discussed.

### 7.3.1 Future Development Areas

This study has focused on the different mooring configuration materials and designs to identify the potential carbon reductions across the industry. The LCA method used excluded some specific areas or drew assumptions on data that was unavailable. Therefore, these areas could be considered in further depth. A detailed case study looking into a smaller number of mooring systems would allow for more rigorous LCA analysis, which could incorporate O&M, decommissioning and a detailed transportation assessment. Potential elements which could extend the analysis in this project are listed below:

- Improve knowledge on the embodied carbon of the testing process involved with mooring lines.
- Complete detailed case studies which include specific transportation routes, manufacturing facility and assembly areas for each different material included.
- Complete a review on the different O&M requirements involved with the different mooring configurations for an entire wind farm design life.
- Review the different decommissioning possibilities and try to calculate the expected emissions through the recycling of components.
- Review the impact on carbon emissions using different grades of steel chain in the mooring design (R3, R4 and R5).
- Review impact of local manufacture, identify key opportunities for Cornwall area.
- Analysing cost reduction opportunities integrated with carbon emission reduction.

# 8 CONCLUSIONS

An impact assessment on the carbon footprint of different floating offshore mooring systems has been carried out to compare the carbon emissions of various mooring configurations and components to identify opportunities for carbon emission reduction for FOW development in the Celtic Sea. Mooring components used on pre-commercial FOW projects have been identified and used to inform the base case mooring configuration designs, along with environmental considerations specific to FOW sites in the Celtic Sea.

The carbon LCA included detailed assessment of the manufacture, fabrication and installation process for mooring system components. The study found that steel chain is currently the most commonly used mooring line component with the greatest associated carbon emissions. It was found that steel chain accounts for 88% of the carbon emissions in a typical 3-line catenary mooring system using drag embedment anchors. The main contributors to the carbon emissions of steel mooring chain suitable for FOW were found to be the manufacturing processes and transportation emissions.

Despite having relatively high manufacturing carbon emissions per unit mass, synthetic rope was found to have significantly lower carbon emissions when used in the mooring system compared to steel chain, due to the reduction in mooring line material mass required. The additional ancillary equipment required in taut and semi-taut mooring configurations add their own carbon emissions to the system, but enable greater emission savings in the system as a whole.

The potential use of more novel anchors and ancillaries have been identified as areas that could offer significant reductions in carbon emissions. Using technologies such as LRDs can allow the length of mooring line to be shorter or the steel chain diameter to be reduced, therefore resulting in a decrease in material and emissions.

The development and commercialisation of mooring solutions using synthetic rope and enabling ancillaries has been identified as a key opportunity to reduce mooring system carbon emissions. Other opportunities in mooring system design to reduce carbon emissions include reduction in ground chain diameter development of novel anchor solutions and standardisation of components.

Opportunities for carbon emission reduction were also identified within life cycle processes, such as raw material production for mooring system components. Carbon emissions produced by the manufacture of steel mooring components can be reduced using clean electricity and a green heat source. The recycling of steel presents the opportunity to reduce carbon emissions from raw material extraction, however current recycling processes and facilities are not capable of recycling steel at this scale in an energy efficient manner. Manufacturing processes for synthetic rope are novel in comparison to steel, and the opportunity for carbon reduction should be explored through the use of bio-based synthetics and through the recycling and reuse of materials.

While raw material and manufacture has been found to be the greatest contributor to mooring system life cycle carbon emissions, further assessment of O&M and end of life considerations in the LCA should be investigated as FOW development in the Celtic Sea reaches commercial maturity.

From the findings of the carbon LCA study performed, and the carbon reduction opportunities discussed, mooring system carbon reduction opportunities for the Cornwall area are identified to support the development of commercial FOW in the Celtic Sea.

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# 10 APPENDIX

Table 31: Full Arrangement Summary

| Configuration Name | Line Type | No. of Lines | Chain Length (m) | Chain Size (mm) | Rope Length (m) | Rope Diameter (mm) | Ancillaries | Anchor Type | Anchor Sizing (Te) |
|---|---|---|---|---|---|---|---|---|---|
| **Base Case Configurations** | | | | | | | | | |
| **Catenary A** | Chain | 3 | 750 | 152 | - | - | - | DEA | 30 |
| **Catenary B** | Chain | 6 | 750 | 132 | - | - | - | DEA | 23 |
| **Catenary C** | Chain | 9 | 750 | 112 | - | - | - | DEA | 12 |
| **Mixed Buoyant A** | Chain, Synthetic Rope | 3 | 400 | 152 | 150 | 230 | Buoyancy Modules | DEA | 15 |
| **Mixed Ballasted** | Chain, Synthetic Rope | 3 | 400 | 152 | 150 | 220 | Clump Weights | DEA | 12 |
| **Taut A** | Chain, Synthetic Rope | 3 | 50 | 152 | 350 | 200 | - | Suction Bucket | 113 |
| **Alternative Configurations** | | | | | | | | | |
| **Catenary D** | Chain | 3 | 750 | 152/114 | - | - | - | DEA | 30 |
| **Catenary E** | Chain | 3 | 750 | 152 | - | - | - | Driven Pile | 41 |
| **Catenary F** | Chain, Steel Wire | 3 | 650 | 152 | 100 | 130 | - | DEA | 25 |
| **Catenary G** | Chain, Synthetic Rope | 3 | 650 | 112 | 100 | 195 | - | DEA | 25 |
| **Mixed Buoyant B** | Chain, Synthetic Rope | 3 | 400 | 152/114 | 150 | 230 | Buoyancy Modules | DEA | 15 |
| **Taut B** | Chain, Synthetic Rope | 3 | 50 | 152 | 350 | 200 | - | Driven Pile | 55 |
| **LRD A** | Chain | 3 | 750 | 81 | - | - | LRD | DEA | 20 |
| **LRD B** | Chain | 3 | 350 | 152 | - | - | LRD | DEA | 20 |
| **LRD C** | Chain, Synthetic Rope | 3 | 250 | 81 | 100 | 195 | LRD | DEA | 20 |

| Configuration Name | Line Type | No. of Lines | Chain Length (m) | Chain Size (mm) | Rope Length (m) | Rope Diameter (mm) | Ancillaries | Anchor Type | Anchor Sizing (Te) |
|---|---|---|---|---|---|---|---|---|---|
| **LRD D** | Synthetic Rope | 3 | - | - | 120 | 200 | LRD | DEA | 25 |
| **Shared Anchor** | Chain | 3 | 850 | 152/ 114 | - | - | - | Suction Bucket | 88 |

# GLOSSARY

Table 32: Glossary

| Term | Definition |
|---|---|
| Carbon Emissions | The total amount of carbon equivalent greenhouse gas emissions, expressed in metric tonnes of equivalent carbon dioxide ($TeCO_2e$). |
| Deep Water | A water depth greater than 100m. |
| Embodied Carbon | Embodied carbon is the carbon dioxide ($CO_2$) or greenhouse gas (GHG) emissions associated with the manufacture and use of a product or service. |
| Greenhouse Gas Emissions | Environmentally harmful gases emitted during a process |
| Mooring Component | Individual piece of mooring equipment e.g. chain |
| Mooring Configuration | The arrangement or setup of the components that make up a mooring system. |
| Mooring System | The group of interacting mooring elements that provide station keeping properties as a unified whole. |
| Shallow Water | A water depth of 100m or below |

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