MOORINGS & FOUNDATIONS

ANALYSIS OF THE INNOVATION LANDSCAPE FOR COST REDUCTION IN SUPPORTING INFRASTRUCTURE

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CONTENTS

Acknowledgements

The authors of this report would like to thank all of the marine renewable energy companies who responded to our Voice of Customer (VOC) sector survey. The survey was sent to 99 companies and was completed by 31 and it provided useful insight into the requirements and perceptions of the sector in relation to mooring and foundation systems. We would also like to thank Oxford Creativity, experts in the problem solving technique TRIZ who facilitated the innovation workshop into mooring and foundation systems, which was also attended by WES. The findings of both the VOC survey and TRIZ workshop are summarised within this Landscaping report.

Executive Summary

Tension Technology International (TTI), was commissioned by Wave Energy Scotland (WES) to conduct a Mooring and Foundation Landscaping Study. The objective of this study was to give an overview of the current landscape, while exploring the potential of mooring and foundation innovations to make an impact on reducing the cost of energy for wave energy converters (WECs). Project partners were University of Exeter and Black & Veatch.

This landscape study demonstrates that there are clear opportunities to make an impact on the cost of energy of wave power through further development and innovation in mooring components, foundations and associated subsystems. The study has been conducted in four main work packages:

- State-of-the-Art (Landscape)
- Voice of the Customer (VOC-Survey)
- Moorings & Foundations Innovation (TRIZ Workshop)
- Mooring & Foundation Case Studies

The four different strands of work provide a range of interrelated perspectives. A state-of-the-art, desk study review was conducted of the current mooring and foundation landscape, including the latest technologies, in addition to a review of design analysis approaches and codes. The Voice of Customer (VOC) survey was conducted to better understand the requirements and priorities of the sector. The basis of the Mooring & Foundations Innovation work package was a TRIZ innovations workshop, which adopted a clean sheet approach, to identify potential new innovation opportunities. Finally, a series of Mooring & Foundation Case Studies were conducted to demonstrate the cost benefits of system compliance for spread mooring systems. A range of device scales, water depths and footprint radii were studied which were compatible with the range of device scales and sites identified by the VOC survey. It was not possible to consider every class of mooring system via the case study assessment, however, the VOC survey confirmed that spread type mooring systems, whether chain catenary or semi-taut synthetic-based systems are a popular choice within the sector. The four-strand approach also helped identify gaps in sector know-how while identifying contradictions for instance, sector requirements and technical viability and affordability.

The combined output of these work streams was then used to identify R&D opportunities which could have a positive impact on the future wave power cost of energy.

State-of-the-Art

A review of the current state-of-the-art was conducted in terms of mooring and foundation requirements and technologies relevant to wave power exploitation. Ten different classes of mooring system were identified and were confirmed via the VOC survey to be broadly representative of what is being considered within the sector today. Of these categories the main attributes, advantages, disadvantages and potential failure modes were assessed. Actual mooring system (including foundation) selection is often driven by the operating mode of the specific WEC technology and site conditions, which from the evidence of the VOC are shown to be quite diverse.

The review also considered key components and subsystems under development which are relevant to the station-keeping of WECs. Due to the challenging nature of the environment which combines variable seabed conditions with shallow water effects it is evident that companies are already innovating and developing potentially enabling technologies which are at various technology readiness levels (TRLs). Some cost-effective solutions already exist such as drag embedment anchoring (DEA) which can have very efficient weight to holding capability ratios, however suitable site conditions are not always available for such solutions.

Based on the level of both industry acceptance and experience and some beneficial working principles (see Section 3.3.2), TTI and partners expect the use of chain or wire rope in moorings (including those for WECs) to continue[1]. We would, however, like to highlight that through partial or full- replacement of chain or wire rope with alternative components (such as synthetic fibre ropes and/or elastomeric tethers), mooring systems capable of delivering appropriate restoring forces for WECs, both in operating and survival conditions can often be devised. Compared to systems comprised entirely of steel components the use of alternative materials can lead to mooring systems which are:

- more compliant in shallow water, leading to a subsequent reduction in mooring loads;
- much lighter (making handling operations easier); and
- much cheaper

These benefits are illustrated in the mooring case study results presented later on in this report.

As part of the state-of-the-art review consideration was also given to mooring system analysis approaches, relevant design codes, condition monitoring and the role of component testing.

Table 1 summarises examples of R&D themes which after review appear important to the sector.

[1] As discussed in Section 3.3.4 despite the existence of well-established design guidance and certification procedures failures still occur due to uncertainties which are not accounted for in mooring system design. For chain and wire based systems these uncertainties include previously unknown failure mechanisms.

Table 1: Examples of the motivation and requirements for research and development.

R&D Themes	Motivation & Requirement
Foundations for rocky seabed	Not all wave sites have sufficiently deep stable sediment for embedment anchors. Requirement for efficient and cost-effective drilled, gravity or hybrid anchoring which is not reliant on expensive offshore vessels or sensitive to limited weather windows.
Alternative mooring components	Although widely used chain catenary mooring systems are heavy, expensive and can have reliability issues. Requirement for lightweight, fatigue resistant solutions which are inexpensive, for example mooring system compliance via line elasticity.
In-line connectors	In-line connectors are lumped mass discontinuities which are common failure points. Requirement for lightweight, fatigue resistant connectors.
Mooring line monitoring	Need for reliable long-term monitoring systems as part of lifecycle management to: i) ensure system integrity, ii) better understand line tensions in this new application for system performance and durability and iii) verify analysis methods and code applicability.
Fairleads and quick release systems	From available data the majority of line failure in oil and gas installations or vessels occur at or near line fairleads. Quick release systems reduce weather risk and downtime. Most WECs require light, reliable and fatigue resistant quick release systems at the top end connection, buoy release point or anchor. A combined electrical and mooring quick connect/disconnect system may allow marine operations to be expedited.
Weather vaning systems & turrets	Wind, waves and currents apply loads from different directions. Depending on the type of WEC, passive or active weather vaning systems can be required to reduce survival loads or optimise power capture.
Active mooring line control	Some WEC technologies have a survival strategy to lower all or part of the system in the water column in survival waves, for others the mooring lines are an integral part of the load path between the foundation(s) and power take off system. Requirement for development of line components which are not vulnerable to bend-over-sheave fatigue and for cost-effective, reliable underwater winching systems.
Marine installation	Requirement to design systems that reduce the need for expensive oil and gas vessels (e.g. offshore heavy lift operations), such as the use of smaller vessels that can work in a wide range of sea-states.
Analysis techniques	Requirement to develop more appropriate numerical tools and design processes for WEC mooring and foundation systems, which are validated using field data.
Design guidelines	Existing offshore guidance may not be relevant to WECs. Need to develop appropriate design criteria that reflects the level of risk and consequency of failure of WECs.

Voice of the Customer (VOC)

As part of the mooring and foundation study a Voice of the Customer (VoC) survey was created to gather the opinions and requirements of the sector on current mooring and foundation technologies. For instance, the VOC survey provided an insight into such requirements as water depth, footprint, device excursion and anchoring preference for a given scale of the device. This also helped to identify and understand the sector perception of technical and economic challenges and highlight opportunities and requirements for innovation. The questions were tailored to help confirm competing design requirements and contradictions, which was also an important aspect of the innovation work conducted as part of the TRIZ workshop. Apparent design contradictions also featured in the Case Studies (e.g. the competing requirements of low mooring system loads and ease of power export). Some of the questions were specifically tailored to the overlapping requirements with the WES Cost Reduction in Supporting Infrastructure – Electrical Connection study in terms of power export requirements and challenges which will also help to inform opportunities for collaborative innovation.

This survey was sent to 99 offshore renewable energy developers and 31 responded of which 75% were WEC developers. Many of these developers have real-world development experience, are at moderate TRLs and have different device designs targeting a wide range of site conditions so their responses are deemed as being interesting and pertinent. Intended mooring systems are also broad-ranging and it is clear that the sector appreciates that there is no "one-size-fits-all" type solution: the mooring system design is intrinsically coupled to the WEC design development and the environmental conditions at the deployment site. Some developers appreciate that this requires engaging with the specialist supply-chain at early stages in the WEC design, but not all.

The cost of purchasing, installing and operating the mooring system (including anchorage) is repeatedly cited as a key issue. The data collected generally shows that WEC developers are generally open to innovative or novel solutions if they can be qualified with high-confidence and achieve cost reductions. The verbal responses to questions generated a useful compendium of risks and challenges faced by the sector relating to moorings and foundations and these responses reinforce the above comments about key R&D areas for the sector.

Key findings from the VOC Survey

The VOC identified several challenges faced by developers such as the dynamic nature of the system, electrical umbilical off-take, running mooring lines over sheaves, vertical loads at anchors in 'hard' sea beds, active/passive weather-vaning and active/passive storm survival strategies. Most of these challenges may be specific to the WEC sector. All of these areas could be deemed worthy of R&D projects.

Pulling together all of the responses on the subject of enabling technology development it can be stated then that key areas for the sector to focus development on include: i) quick connect-disconnect systems for electrical cables and mechanical connections, ii) anchoring solutions in wide range of geotechnical conditions under dynamic (and potentially vertical) loads and iii) mooring line compliance improvement sub-systems.

Mooring & Foundation Innovations

The TRIZ[2] workshop was a fast paced introduction and application of TRIZ principles to the challenging area of cost reduction in WEC mooring and foundation systems. The team who participated in the

[2] Theory of Inventive Problem Solving (approximate translation from Russian).

event covered a wide-range of experiences and knowledge. This ensured enough breadth of experience to 'break' the psychological inertia of the experienced hands and bring in fresh perspectives and knowledge from other sectors. Meanwhile the experienced hands could frame the problem, previous concepts and solutions and think beyond the limits of the current state-of-the-art. With this mix the workshop was wide-ranging and as reported generated almost 200 ideas, although that does include some repetition.

The use of TRIZ does not automatically yield "light-bulb moments", however, by the end of the workshop when all the ideas were brought together and viewed as a whole it was clear that a thorough and useful exercise had occurred. This report has attempted to summarise the process and the outcomes of the workshop. As this is the work of a small team it is hoped that this will provide inspiration to the readers and yield further fruitful paths of idea generation. Further it is hoped that the introduction to the TRIZ process is new for some readers and provides access or introduction to a useful tool for the wave energy sector.

Key findings from the Mooring & Foundation Innovation Study

The main outcome from the Mooring & Foundation Innovation Study is a Pugh matrix which comprises a set of ideas that have been ranked against the three criteria (practicality, R&D effort and cost impact). These ideas have strong potential to achieve the cost reduction objectives and could be worth focused R&D effort to take them to higher Technology Readiness Levels for the wave energy sector.

MOORING & FOUNDATION CASE STUDIES

The purpose of the scenario-based study was to show the techno-economic impact of mooring compliance on the M&F system including weight, installation requirements and relative cost of energy based on data and assumptions that can be readily substantiated. Studies on a total of 416 different scenarios were conducted using sector standard mooring analysis software in combination with coded optimisation and cost tools. The impact was assessed for a range of WEC scales, water depths, footprints and foundation types, with comparisons made on two spread mooring systems; a semi-taut nylon-based system and a chain catenary system. It is recognised that these are not the only solutions for providing station keeping, however the VOC survey confirmed that these classes of moorings are being considered by a significant proportion of the sector. Variations for spread mooring systems include combinations of wire, other synthetics, clump weights, buoys, shock absorbers etc[3]. For this study only three types of anchor were considered namely: gravity base (GBA), drag embedment (DEA) and vertical uplift anchor (VLA). No consideration was given to piling or rock anchoring and it is recognised that suitability and cost of these approaches can be very site specific. At a high-level the study provides a benchmark for the development of alternative innovations for mooring compliance and identifies the economic opportunity for utilising other types of foundations. The following parameter trends in Table 2 were investigated.

[3] It was not practical to compare all these options within this study, also for newer mooring innovations it was not possible to substantiate their performance and costs or determine how scalable the technologies are to withstand the larger loads associated with larger displacement devices considered in this study.

Table 2: Key findings from the mooring and foundation scenario study.

Parameters compared	Observed Trends
Influence of compliance on line minimum break load (MBL[4]) with device scale	Increasing system compliance can potentially lead to significant reductions in required line minimum break load (MBL), line costs and loads experienced by the WEC and anchor. Generally, having a greater mooring system compliance led to lower line loads, however, this was not always the case.
Influence of footprint on line MBL with line type	In addition to rope stiffness, mooring footprint was a powerful lever for reducing mooring loads.
Influence of water depth on line MBL with line type	There was a clear benefit (in terms of required line MBL) in adopting a compliant system for all of the water depths considered. This benefit was magnified when the lower unit cost of nylon for a given MBL is considered. A limited number of chain-based solutions were found for the largest device scale in shallow water depths, suggesting that only a taut-synthetic option would be feasible in these scenarios.
Impact of MBL requirement on mooring line weight	The synthetic-based systems had a much lower weight compared to the conventional chain systems for the four water depths studied. The increased compliance of the lower stiffness ropes resulted in lower line tensions and subsequently a lower required MBL rating (i.e. smaller and lighter ropes). As expected opting for higher-grade chains allowed for smaller, lighter chains to be specified and hence a lower total system weight than lower grades. The weight saving of adopting synthetics can be an order of magnitude, resulting in promising transportation, installation and decommissioning savings.
Impact of MBL requirement on the cost of mooring lines	For most device scales and water depths there were substantial cost savings in adopting synthetic ropes over chain. Although the savings were less pronounced for the smallest device scale.
Comparison of device maximum excursions with total lines costs and characteristic line tensions	Compliant mooring systems with large footprints tend to lead to large device excursions. However a like-for-like comparison of nylon and chain case studies indicated that for low footprint-water depth ratios synthetic systems tend to have: i) similar maximum surge excursions, ii) lower line tensions and iii) lower total line costs. In some cases increased compliance can lead to larger device excursions as well as lower line tensions and costs. In terms of the relative LCOE there are significant benefits in utilising compliant mooring components instead of chain and these benefits are even more significant when DEAs or VLAs are used over conventional gravity base anchors.
Comparison of foundation mass with type	For the cases considered there are significant weight savings (up to two orders of magnitude) in adopting embedment anchors over gravity based anchors which is expected as the former have very efficient weight to holding capacities. Some of the gravity based anchor examples are clearly not practical or affordable and highlight the need for the development of rock anchoring solutions when suitable sediment is not available for embedment anchors.

[4] In this report minimum break load (MBL) and breaking load (BL) are interchangeable terms.

Parameters compared	Observed Trends
Comparison of foundation cost with type	There are significant cost benefits in adopting embedment anchors over gravity based anchors and this is due to the relationships between bulk material cost, weight and holding capacity for each technology.
Installation costs	The type of anchor selected had a large effect on the overall capital costs. In particular, the size and weight of gravity based anchors showed significantly higher costs compared to the embedment anchors.
System mean time to failure (MTTF)	Very high and potentially unrealistic MTTF time-scales were calculated. However, the calculations were based on limited mooring and foundation failure rate data in the public domain and more reliability data sharing across the offshore sector is required.
Levelised cost of energy (LCOE)	In all of the cases studied the levelised cost of energy of the taut-synthetic mooring systems were more cost-effective than the catenary chain systems. Although historically the mooring and foundation cost centre has been estimated as ~10% of the overall LCOE, this study demonstrated that there can be significant variations (with levelised costs of up to ~40% in extreme cases).

Data from all of the simulation runs were then analysed and selected trends plotted. In addition a levelised cost of energy (LCOE) analysis was completed on 89 cases as part of an assessment of the financial impact of mooring and foundation system design choices on the overall cost of WEC projects. Multiple influencing factors were considered; including the cost per tonne of steel, average generation (kW) capacity per tonne (of WEC device mass), failure rates (of the mooring and foundation components), and the capacity factor of the wave energy technology. In total, 89 cases from the previously obtained results were analysed and trends within the data sought to establish the impact of the aforementioned parameters on the LCOE of wave energy projects.

LIST OF ABBREVIATIONS

3-T	Tension, Time and Temperature
ABS	American Bureau of Shipping
AHV	Anchor Handling Vessel
ALS	Accidental Limit State
B&V	Black and Veatch
CALM	Catenary Anchor Leg Mooring
CAPEX	Capital Expenditure
CBOS	Cyclic Bend Over Sheave
CFD	Computational Fluid Dynamics
COTS	Commercial-off-the-shelf
DEA	Drag Embedment Anchor
DGPS	Digital Global Positioning System
DNVGL	Det Norske Veritas Germanischer Lloyd
DoF	Degrees of Freedom
EA/BL	Axial Stiffness to Break Load ratio
EMEC	European Marine Energy Centre
ETI	Energy Technologies Institute
FEA	Finite Element Analysis
FLS	Fatigue Limit State
FOWT	Floating Offshore Wind Turbine
FPSO	Floating Production, Storage and Offloading
G3, G4	Grade 3, Grade 4
GBA	Gravity Based Anchor
HMPE	High Modulus Polyethylene
IEA	International Energy Agency
IMU	Inertial Motion Unit
IWRC	Independent Wire Rope Core
JIP	Joint Industry Project
LCOE	Levelised Cost of Energy
M&F	Mooring and Foundation
MAIB	Marine Accident Investigation Board
MBL	Minimum Break Load
MCA	Maritime Coastguard Agency
MEC	Marine Energy Converter
MESAT	Marine Energy Supporting Array Technologies
MODU	Mobile Offshore Drilling Unit
MRCF	Marine Renewables Commercialisation Fund
MRE	Marine Renewable Energy
MTTF	Mean Time to Failure
NDT	Mean Time to Failure
NERC	Natural Environment Research Council
NPV	Net Present Value
O&G	Oil and Gas
OC	Oxford Creativity
OES	Ocean Energy Systems
OPEX	Operational Expenditure
PTO	Power Take Off
R&D	Research and Development
RIDDOR	Reporting of Injuries, Diseases and Dangerous Occurrences Regulations
ROV	Remotely Operated Vehicle
RPN	Riser Protection Net
SALM	Single Anchor Leg Mooring
SE	Scottish Enterprise
SLS	Serviceability Limit State
SPM	Single Point Mooring
TCLL	Thousand Cycle Load Level
TEC	Tidal Energy Converter
tf	tonnes-force
TLA	Tether Latch Assembly
TLP	Tension Leg Platform
TRIZ	Theory of Inventive Problem Solving (*translation)*
TRL	Technology Readiness Level
TSB	Technology Strategy Board
TTI	Tension Technology International
UK	United Kingdom
ULS	Ultimate Limit State
UoE	University of Exeter
VIV	Vortex Induced Vibration
VLA	Vertical Load (plate embedment) Anchor
VOC	Voice of Customer
WEC	Wave Energy Converter
WES	Wave Energy Scotland
WLL	Working Load Limit

1 INTRODUCTION

1.1 BACKGROUND

The Wave Energy Scotland (WES) programme supports technology development which targets risk and cost reduction associated with the structure, prime mover, power take-off and control; representing an estimated combined 45% of typical project costs.

The supporting infrastructure associated with Electrical Connections and Moorings & Foundations for wave energy projects represents a significant proportion of total wave energy project costs (8% and 11% of total project costs). These two areas, therefore, represent a significant target for cost reduction which would improve the competitiveness of wave energy projects using existing technology or technology currently in development. Furthermore in 2017 the Energy Technologies Institute (ETI) set the following challenge:

"*Wave energy can work technically and has been proven through a small number of installations, but it is presently up to 10 times more expensive than other low carbon alternatives so there needs to be a radical rethink if it is to become cost competitive."* (ETI[5], 2017)

WES's current requirements are divided into two areas:

• Cost Reduction in Supporting Infrastructure – Electrical Connection

• Cost Reduction in Supporting Infrastructure – Moorings & Foundations

This report specifically addresses the second requirement.

For the purposes of this study of Moorings & Foundations the scope shall be defined as the whole extent of the station keeping system up to the connection point of a wave energy converter (WEC). Benefits to the wave energy converter and onboard subsystem design changes facilitated by improvements to the station keeping system are considered in scope.

1.2 PURPOSE

The purpose of this landscaping study is to advise WES on the current state-of-the-art for the station keeping of WECs and identify specific innovation opportunities which have a high potential to improve the levelised cost of energy (LCOE) for wave energy. It is expected that the findings of this report will be used to help inform future WES funding calls in relation to moorings and foundations.

The purpose of this document is not to be a mooring and foundations design manual or provide design guidance which is already covered in existing design codes. However, consideration is given to development and relevance of the codes to the wave energy sector. The report can help to guide developers, who may have limited expertise in moorings and foundations (M&F), to understand the challenges encountered during M&F design and subsequent project phases, and which elements may be the best initial focus for cost reduction.

[5] ETI (2017) *"ETI sets out priorities for marine energy if it is to compete with other low carbon sources"* Accessed online: https://www.eti.co.uk/news/eti-sets-out-priorities-for-marine-energy-if-it-is-to-compete-with-other-low-carbon-sources.

2 PROJECT OVERVIEW

2.1 PARTICIPANTS

The landscaping study has been led by Tension Technology International Ltd (TTI). Established in 1985 to support the Oil & Gas industry, TTI is an independent consulting group specialising in the design of mooring systems and products for floating structures designed to operate in the severest ocean environments. Over the past twenty years TTI has provided expert advice to the marine renewables sector including wave, tidal and offshore floating wind installations. TTI leads a number of technology innovation programmes for the development, testing, qualification and commercialisation of new mooring and anchoring products designed for improved operability, array densities, reliability and cost of energy. TTI has its own in-house testing capability for loading and fatigue tests as well as overall Highly Accelerated Life Testing (HALT) testing, which is used to develop and qualify new mooring products. TTI works very closely with rope and chain suppliers and classification societies to develop and qualify these systems. This project has been managed by Ben Yeats and Tom Mackay with additional technical input from the wider TTI team including Stephen Banfield and Jack Evans.

The two other principal project partners, under subcontract to TTI, are the University of Exeter (Renewable Energy Group, Penryn campus) and Black & Veatch. The University of Exeter has a track record in research, simulation and testing of mooring system and components for marine renewables. Key team members were Professor Lars Johanning and Dr Sam Weller. The University of Exeter was involved in the development of an integrated mooring and foundation tool for large-scale deployments of MRE devices, as part of the DTOcean project. This tool has been adapted for the scenario-based study, for the costing of mooring and foundation systems across a range of generic WEC scales and water depths. This information was then fed to Black & Veatch to perform a relative assessment of the impact of mooring compliance and foundation selection on levelised cost of energy (LCOE). This work was led by Dr Adrian de Andres with input from Ian Stacey. Engineering consultants Black & Veatch has considerable experience in the sector and have worked with a large number of technology developers including specialising in the economics of wave power.

The principal authors of this report are Ben Yeats, Tom Mackay and Dr Sam Weller.

2.2 APPROACH

The study was subdivided into four interrelated strands with associated aims:

- ***State-of-the-Art:***
  The aim of the review was to establish and document existing experience and the state-of-the-art for mooring and foundation technologies relevant to the wave energy sector. While reference is made to relevant existing and transferable technologies, a primary focus was to identify new mooring and foundation technologies that have good potential reduce this LCOE cost centre with further development. Utilisation of these technologies may also provide indirect cost reductions of other LCOE cost centres, for example having a positive effect on WEC operational efficiency, maintainability, availability and survivability.

- ***Voice of the Customer Survey:***
  An online Voice of the Customer (VOC) survey was designed to collate the sector mooring and foundation requirements, challenges and general perspectives of wave technology developers. The survey was also opened to tidal and offshore floating wind sectors which have similar

requirements. This helped to identify the challenges, design contradictions and research priorities of the sector.

- ***TRIZ Innovation workshop:***
  TRIZ was adopted to provide a structured framework to innovation and problem-solving. TRIZ is a Russian acronym which roughly translates to the "Theory of Inventive Problem Solving". The workshop was attended by project partners and WES team members and was facilitated by TRIZ specialists Oxford Creativity. The workshop aimed to overcome any psychological inertia due to the previous experiences of the team members and approach the potential for innovation with fresh thinking via formal brainstorming exercises. The ideas and innovations generated via the workshop were then evaluated in terms of technical maturity and ranked to assess their potential to impact on the overall cost of energy by TTI.

- ***Mooring case studies for specific scenarios:***
  Due to the diversity of WEC types and site conditions it is not practical to consider every mooring and foundation scenario. One of the recurring requirements for spread moorings, as confirmed by the VoC survey, is the reduction of floating structure mass and mooring and anchor loads via compliance. It was therefore decided to run a number of case studies benchmarking a conventional chain mooring against a semi-taut mooring with compliance provided by axial stiffness rather than catenary geometry. This study was conducted using dynamic mooring analysis software and developed tools for a range of generic device scales, water depths, mooring footprints and a range of line compliances. Due to the diverse range of PTO system types currently being considered, in order to keep the analyses generic this subsystem was not considered. It is however acknowledged that PTO systems can significantly influence the coupled dynamics of the device-mooring system. The primary aim was to identify trends across the scenarios in terms of mooring and foundation loads and capital expenditure (CAPEX) and quantify the potential benefit of increased compliance. Output data was also used to assess the potential impact of increased compliance and foundation choice on the levelised cost of energy (LCOE). This work also aims to provide examples of typical design loads for mooring and foundation systems, which in itself will help inform product development for different device scales, footprints and water depths.

Figure 1 describes the overall process. The flowchart shows that data emanating from the four main strands of work was evaluated to identify and evaluate the benefit of enabling technologies and innovations. The findings were then used to identify future research and development (R&D) avenues worthy of future prioritisation.

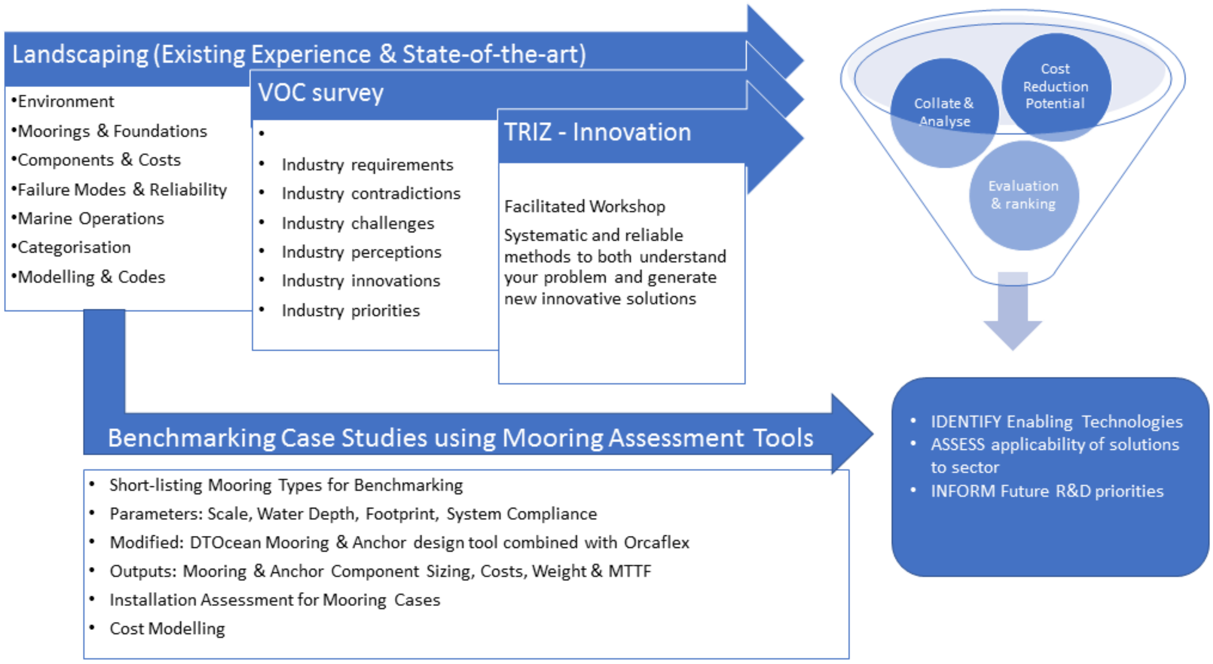


Figure 1: Landscaping Study process flowchart

2.3 Overview of Challenge

The following section provides an overview of the mooring and foundations challenges and opportunities for the marine renewable sector. There is a broad range of WEC device scales being developed with displacements ranging from tens of tonnes to tens of thousands of tonnes.

While there are significant overlapping themes in the mooring and foundation requirements between offshore oil and gas (O&G), floating offshore wind turbines (FOWT), tidal energy convertors (TECs) and WECs, there are also significant differences. These differences are largely due to the distinct environmental design and operating conditions associated with the different technologies. For example, the mooring loads experienced by WECs in highly dynamic wave environments tend to be influenced by wave loading at first-order frequencies (which are typically exploited for power extraction in one or more modes of motion) as well as lower and higher frequencies. Indeed the mooring and foundation system (see Figure 2) can be designed to advantageously influence the response of the device (and hence level of power capture) in relation to the incident wave conditions. This is a fundamental difference with FOWT, TECs and O&G equipment which tend to avoid wave excitation for operational reasons.

Some WECs are designed with PTO systems integrated into the mooring load path meaning that the foundation or anchors, mooring line components, PTO and structure are all subject to highly dynamic load regimes. Conversely other WEC designs incorporate multiple PTO systems on a common structure and the mooring and foundation requirements for this type of device may be for station-keeping only. Furthermore the mooring requirements of a large pitching or heaving system are very different from devices which utilise the seafloor to provide reaction forces (ground referencing systems).

Despite the diversity in WEC designs, in common with the O&G sector, there is a trend towards the use of synthetic based mooring systems due to their potential to be more cost effective, lighter and more reliable than conventional steel components. Commercial rope constructions offer a broad range of properties, e.g. from compliant (nylon) to stiff (high modulus polyethylene, HMPE) materials, the latter of which could be used for ground reference or tension leg platform (TLP) type structures. Conventional O&G mooring and foundation technologies are not always transferable or economically viable for WEC devices due to the environmental conditions and seabed characteristics of the site. Other WEC mooring requirements that may be required include: i) reliable line tensioning systems, ii) quick release/hook-up systems (to maintain the required level of system availability), iii) a survival strategy for storm events and iv) weather-vaning systems (to improve the power capture in operating conditions or reduce extreme loads).

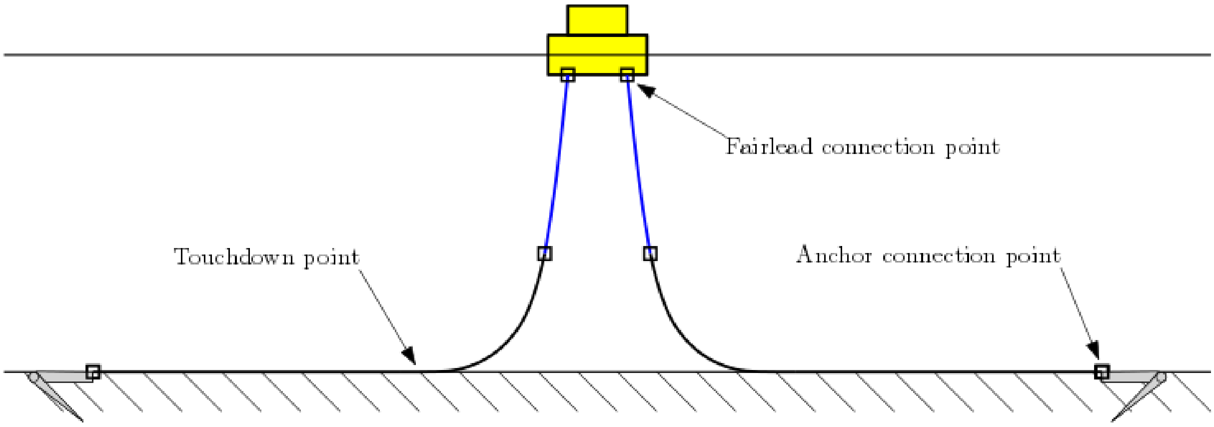


Figure 2: Schematic of an example mooring system showing fairlead and anchor connections and touchdown points (source: TTI).

The variable nature of the seabed, particularly across large array sites also presents several challenges for anchoring. The sediments required for cost-effective drag embedment anchoring can be migratory and hence not always relied upon. Fixing anchors to a rocky seabed can also be challenging due to the variable overburden of sediment. As the sector looks to more compact mooring footprints to improve array densities and reduce the impact on other stakeholders this can present more challenges on the anchoring systems due to an increase in their vertical load component and potential for line-umbilical clashing. Large anchoring and foundation systems can also be expensive to install.

3 STATE-OF-THE-ART

3.1 WEC DIVERSITY AND MOORING & FOUNDATION SYSTEM REQUIREMENTS

There is significant diversity in the design and operating mode(s) of WECs. Unlike the wind energy sector, the wave energy sector is less mature has not yet experienced the same level of technology convergence[6]. The diversity of WEC designs and range of site conditions results in a large assortment of mooring and foundation solutions which are described in more detail in the next section. The size of WECs can range from several tonnes to thousands of tonnes displacement. The operating mode(s) of a given wave technology can directly influence the design of the mooring and foundation system and vice versa. For example, some devices require a mooring and foundation system for station-keeping purposes only and hence there can be synergies with conventional offshore systems which try to avoid resonant structure responses (Figure 3). Other devices utilise the mooring and foundation system directly for one or more power generation modes. In this case developers may seek to tailor the mooring and foundation system in order to achieve resonant device responses in order to maximise power generation (e.g. due to first-order wave excitation). Altering the system's natural frequency may affect the loads experienced by the device as well as the mooring and foundation system and generally developers seek to reduce these loads where possible. Some moorings require minimal forces to be transmitted via operating modes (such as those which comprise one or more power take-off modules supported by a common platform), while others may be directly ground referencing.

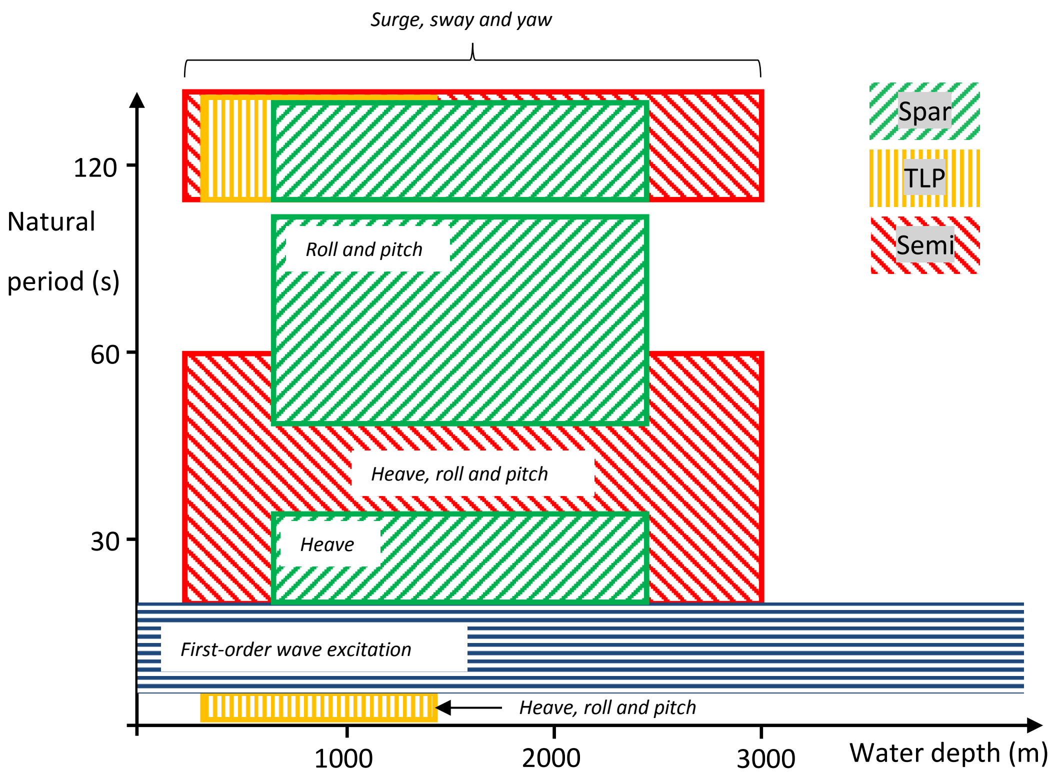


Figure 3: Indicative natural periods of offshore structures and first-order wave excitation periods which may be relevant to WECs. Reproduced from [1].

[6] Indeed convergence to one system type (akin to the three-bladed horizontal axis turbine) may not occur due to differing site requirements and/or device function.

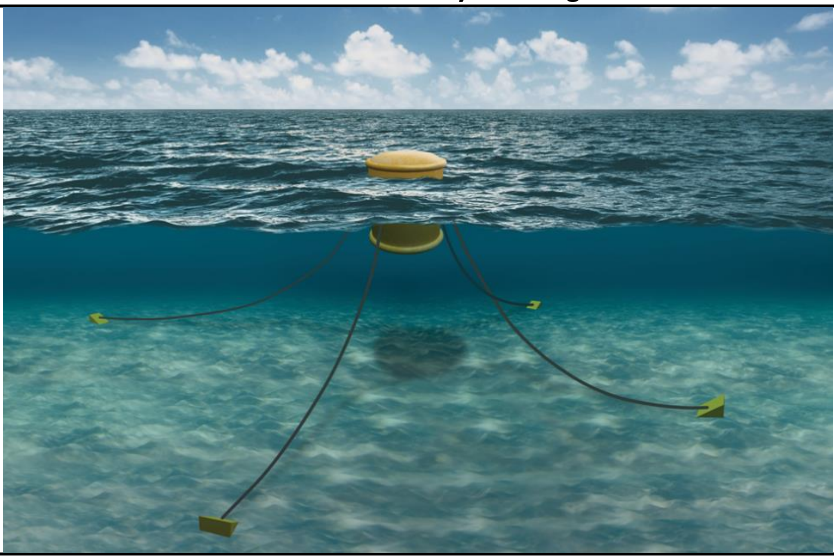
The range of WEC technologies and associated mooring requirements currently being considered is covered in Section 4. With this diversity in mind, there are several general requirements for the mooring and foundation system:

- Capable of holding WEC on station across the range of environmental conditions that a device could experience over the lifetime of the project.
- Has some inherent redundancy in case of line failures.
- Comprises components with an appropriate level of reliability.
- Is straightforward to install, maintain and decommission.
- Is easy to connect and disconnect a device to (particularly important for early stage devices which may need to be installed or demobilised more frequently than a proven technology).
- Isn't prohibitively expensive in terms of component and installation CAPEX and OPEX.
- Can accommodate rise and fall of water level due to tidal variations or storm surges (if the device cannot be fully submerged).
- Either has minimal (negative) impact or maximises power capture.
- Easy to demonstrate as being appropriate to industry regulators so can be qualified/certified.
- Makes efficient use of the consented seabed footprint.
- Either has minimal (negative) or positive environmental impact.
- Has minimal impact with other stakeholders (water-users).
- Can accommodate a power take off umbilical without unhelpful interactions with it e.g. vortices generated by a line interacting with umbilical.
- Enable sufficient device motions for power capture without exceeding the minimum bend radius or axial strength of the umbilical.
- Can easily be adapted for different locations (limiting the extent that moorings have to be redesigned for each individual device deployment).
- Allows mooring and/or foundation component sharing between multiple devices.

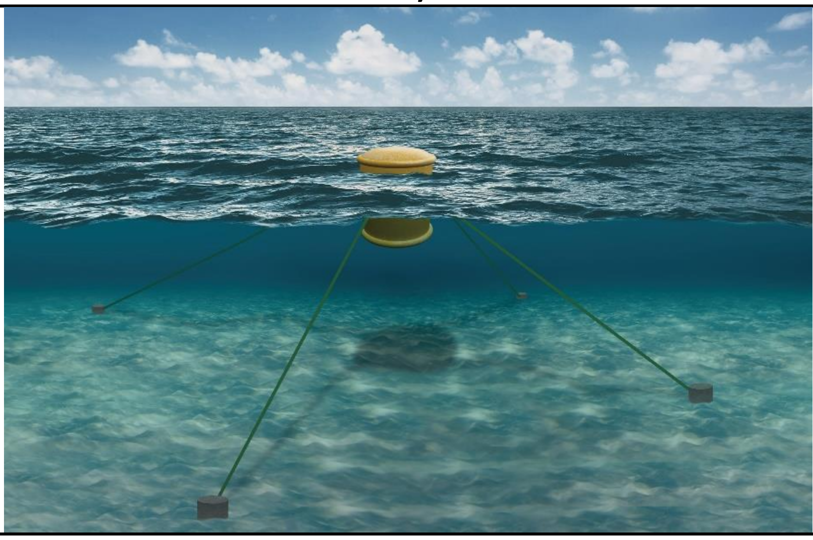
3.2 Mooring System Categorisation

The diversity of WEC type, scale and station-keeping requirements highlights the need for careful selection of research priorities which will have the best potential for the long-term reduction in the cost of energy. There is consequently a large range of mooring system technologies available to the developer and the following sections identify ten different generic mooring categories and highlight the advantages and disadvantages of each system.

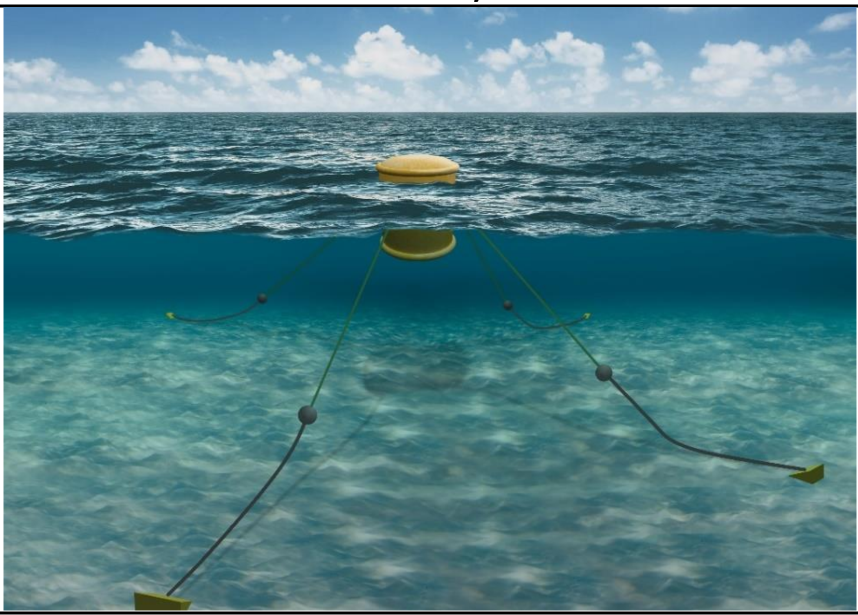
3.2.1 #1 Catenary Mooring

#1 Steel Catenary Mooring

Description: Most conventional mooring system commonly used in O&G industry. The reaction and restoring forces are provided by the mass of the steel chains used and also, in some cases, the elasticity of the chain itself. The mass must, in turn, be reacted by the device buoyancy. Wire combined with chain could be utilised
Advantages: • Conventional materials and mooring components readily available commercially-off-the-shelf (COTS). • Characteristics and design issues well understood and standards published. Catenary mooring provides an efficient form of device position restoration to wave loads and provides some compliance behaviour across certain water depths
Disadvantages: • Highly non-linear stiffness attracts large loads from wave-induced surge motions hence high strength and/or large size chain is needed. • Heavy chain lines have to be supported by the buoyancy of the WEC device. • Large footprint due to line scopes (of 8 or more lines) needed to avoid uplift at anchors. • Likely to be the costliest of all line types because of the heavy all-steel components. • Impractical in shallow water depths and exposed sites – due to high mooring loads • Steel components are subject to corrosion and fatigue failures which are well documented • Not always compatible with high-density arrays due to the footprint size. • Heavy chain can be relatively expensive to handle, transport and install and can impact on vessel size (e.g. the required storage capacity of the chain locker). • Very large and heavy chain on shallow single point moorings (SPMs) have suffered severe link-link wear. • Chains can suffer from snatch loading when the line dynamics are not in phase with platform motions.
Key failure modes/risks: • Significant number of chain and associated connector failures in O&G industry. • Majority of failures occur at connectors or discontinuities. • Out-of-plane bending caused by constrained links • Corrosion and wear on chain links, pear links and shackles. • Insufficient compliance in the system causing excessive snatch loads • When combined with wire - failure at wire socket termination or torsion failures

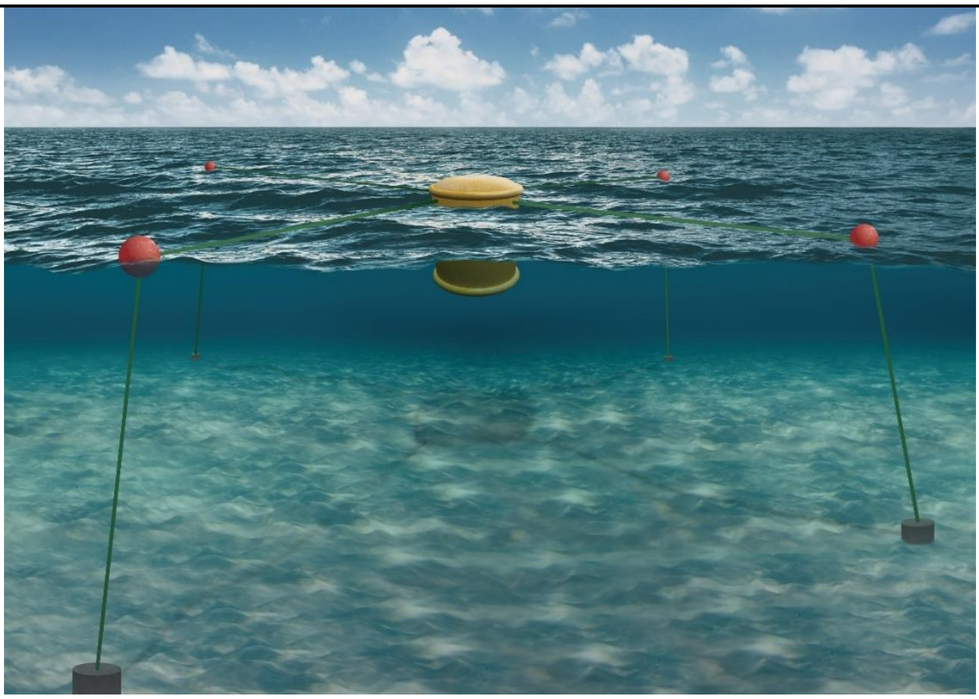
3.2.2 #2 Taut Synthetic

#2 Taut Synthetic

Description: The synthetic rope taut mooring concept was pioneered in deep water moorings for offshore drilling and production platforms. Using synthetic lines – typically polyester – provides system compliance, which is more linear in behaviour than chain catenaries. The lower axial stiffness of nylon is particularly attractive for wave energy sites, where hydrodynamic loading on the mooring system tends to be dominated by first-order motions (e.g. in surge). Pretension requirements and line angles normally result in vertical load component at anchor (requiring VLAs). If the footprint is made larger and the ropes are more spread, the use of DEAs is possible. To keep the loads at the anchors horizontal, it is possible to use ground chain between the synthetic section and the anchor and add a clump weight on it to maintain the last section of chain on the seabed.
Advantages: • For the same break load synthetic rope materials are considerably cheaper than steel wire rope or chain. • Nearly linear system stiffness characteristics leads to better control of mean offsets and loads originating from wave-induced surge motions. • Has the potential to achieve a relatively compact footprint (anchor radius). • Can allow the design of relatively small horizontal offset with respect to electrical umbilical design limitations. • Recent developments have shown that synthetic ropes can be used as a direct replacement for steel wire (e.g. Seine nets and crab lobster pots used in the fishing industry). • Increased abrasion resistance means that some designs can be buried in the seabed (e.g. for buried anchors). • There are many examples where synthetic ropes perform better than steel, see Section 3.3.3.
Disadvantages: • Synthetic rope lines are less robust than chain against abrasion wear and cuts. • Careful fibre selection and rope design expertise needed to achieve a good mooring. • This system tends to require anchors capable of resisting vertical loading. Vertical load anchors are an option if sufficiently deep and stable sediment exists. Otherwise, gravity base or piled anchors are required.
Key failure modes/risks: • Risk of damage to the line during handling during installation and recovery (e.g. abrasion, cuts, creep, heating, wear to the sleeve wear and splices). • Design loads potentially over- or underestimated due to the limitations of modelling these materials within software. • Line pretensions not maintained if creep occurs. • If a clump weight is used, its connection may fail as it is a discontinuity. If it lifts off the seabed, unpredictable tension cycles will occur. NOTE: risks for synthetic ropes apply to other mooring components and systems

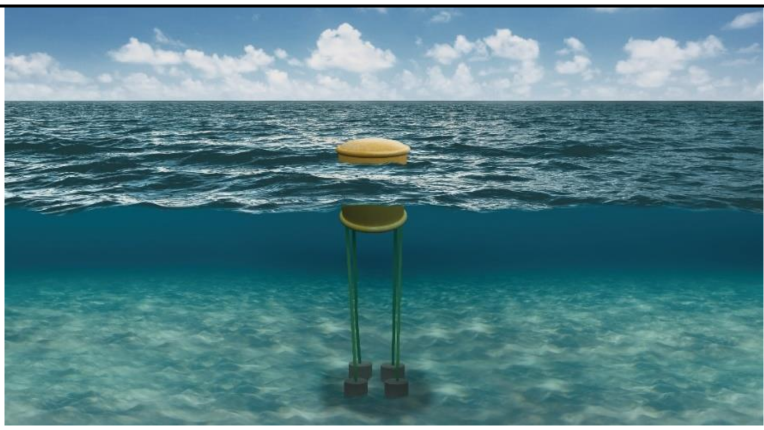
3.2.3 #3 Semi-Taut Synthetic

#3 Semi-Taut Synthetic

Description: The semi-taut synthetic rope and chain mooring may be considered a hybrid system with characteristics of both a catenary and taut mooring. Like the fully taut concept, it has been used by the offshore industry for deep water moorings where all steel mooring lines would put too much weight on the vessel (e.g. in the Gulf of Mexico). The key benefit over category #2 would be that this system allows the use of conventional drag embedment anchors due to the near horizontal force at the anchor. This may be important if an anchor capable of vertical loading is impracticable or too expensive for the given site.
Advantages: • Better system stiffness characteristics than the all chain catenary system and hence can give a workable design with lower strength components. • Synthetic rope has a lower cost per metre than chain for a given minimum break load (MBL). • Easier to handle during installation.
Disadvantages: • Similar overall footprint (anchor radius) to the all chain catenary system. • Synthetic rope lines are less robust than chain against abrasion wear and cuts. • Careful fibre selection and rope design expertise needed to achieve an adequate mooring.
Key failure modes/risks: • As this is a hybrid synthetic /chain system the causes of failure similar to both #1 and #2. • It may be more susceptible to minimum tension cycles than the more highly pre-tensioned system #2.

3.2.4 #4 Buoy Assisted Taut-Leg Mooring

#4 Buoy Assisted Taut-Leg Mooring

Description: Mid-line buoys are introduced to add compliance to the system in survival seas, and can provide station-keeping in operating seas. For some WEC operating modes there may be a benefit that the lines attaching to the device can be near-horizontal. The buoyancy can facilitate hook-up and unhook of the system. Steel chain and wire can be used for the risers to buoy, although lightweight floating synthetics are preferred for between the buoys and WEC. Midwater or surface buoys can be used. This mooring becomes an option if there is a requirement to reduce the mooring system footprint, or seabed conditions don't exist for DEAs.
Advantages: • Easy to hook, unhook mooring. • Good station keeping in operating conditions. • Heave motions are decoupled from mooring so may suit the operating mode of some wave energy systems. • Good opportunity to reduce the anchor footprint.
Disadvantages: • Buoys attract hydrodynamic loads in waves and strong surface currents. • Can lead to a design spiral of requiring bigger and bigger buoys, to avoid snatch loads, which ultimately leads to bigger anchor loads. • More components and connections which can break or become fatigued. • Anchoring loads can be higher than what is permissible with a DEA.
Key failure modes/risks: • Greater number of connections and components present risk of failure. • Mid line buoy can result in additional dynamic loads being imposed on lines and connectors, particularly at a high energy wave site.

3.2.5 #5 VERTICAL TETHER TENSION LEG

<table>
<tr><th>#5 Vertical Tether Tension Leg</th></tr>
<tr><td></td></tr>
<tr><td>Description: This concept is analogous with offshore O&G TLP-type moorings. It offers by far the smallest mooring footprint and utilises the device buoyancy to provide the mooring restraint and restoring forces. The system can provide large lateral compliance although this depends on device buoyancy and water depth The system requires vertically loaded anchors of significant capacity which are likely to be the key cost driver for this system and may not be technically or economically viable (although this will depend on the site conditions). The mooring lines (tethers) must either have sufficient compliance to accommodate tidal variation, have other systems added to compensate for this or be fully submersible. For WEC devices, in particular, the influence of this mooring on performance must be determined as it suppresses heave and pitch motions. TLP type moorings tend not to be adopted for large-scale (+1 MW) wave energy devices. The ratio of extreme wave height to water depth for shallower wave sites, makes TLP type mooring challenging due to snatch loading. While TLP type moorings allow devices to be tightly packed, there may be diminishing returns as the high-density arrays may become wave resource constrained. It is recommended that reference is made to experiences in offshore wind technology as some developers are adopting TLP technology (e.g. Iberdrola’s TLPWIND project). TLP technology may be more viable for offshore floating wind as the sub-structure can have a smaller displacement or more ‘transparent’ shape as they are designed for load shedding rather than wave energy capture.</td></tr>
<tr><td>Advantages: • A laterally compliant system that mobilises the buoyancy of the moored WEC to provide the mooring restraint. • Minimal seabed footprint – lowest of all the mooring system categories by a considerable margin. • Tethers can be steel (deeper waters) or synthetic ropes in shallow waters. • Potentially low mooring cost – predominantly dependent on the anchoring cost.</td></tr>
<tr><td>Disadvantages: • Requires sufficient device buoyancy to pretension tethers, but large water-plane area increases tether loads. • Needs sufficient water depth and tether axial elasticity to accommodate tidal range, additional compensation system or fully submersible device. • Significant risk and cost is transferred to VLA design (e.g. piling). • Could impact on the operating mode of the wave energy device (e.g. no heave compliance). • Socket terminations for large fibre ropes have not yet been developed for TLP tendons, and this would require an expensive development and testing programme. At these scales, carbon pultruded rods are used. Spliced rope terminations can be used but these do not perform as well as flex connector joints.</td></tr>
<tr><td>Key failure modes/risks: • Zero load cycles (snatch) leading to tension-compression fatigue or dynamic overload in mooring line. • High-frequency resonance of lines made from stiff materials possible.</td></tr>
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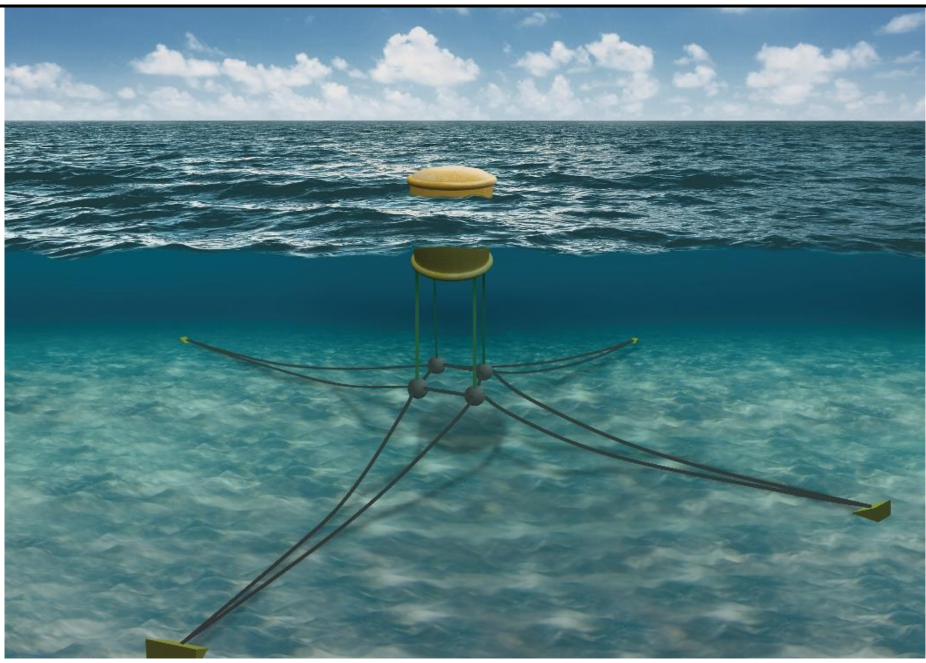
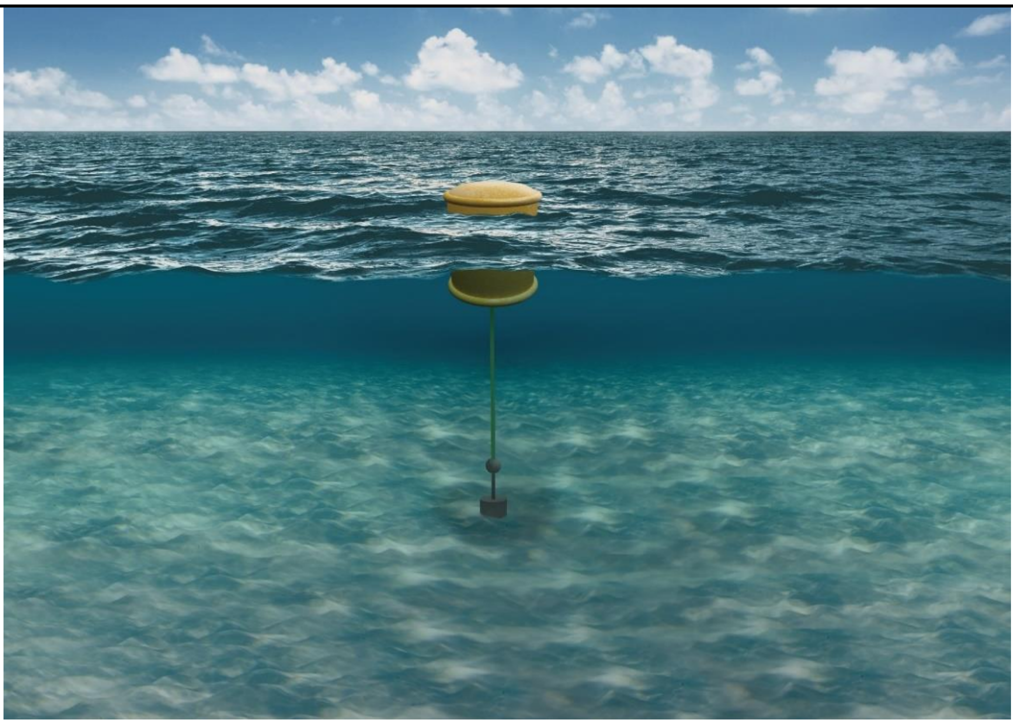
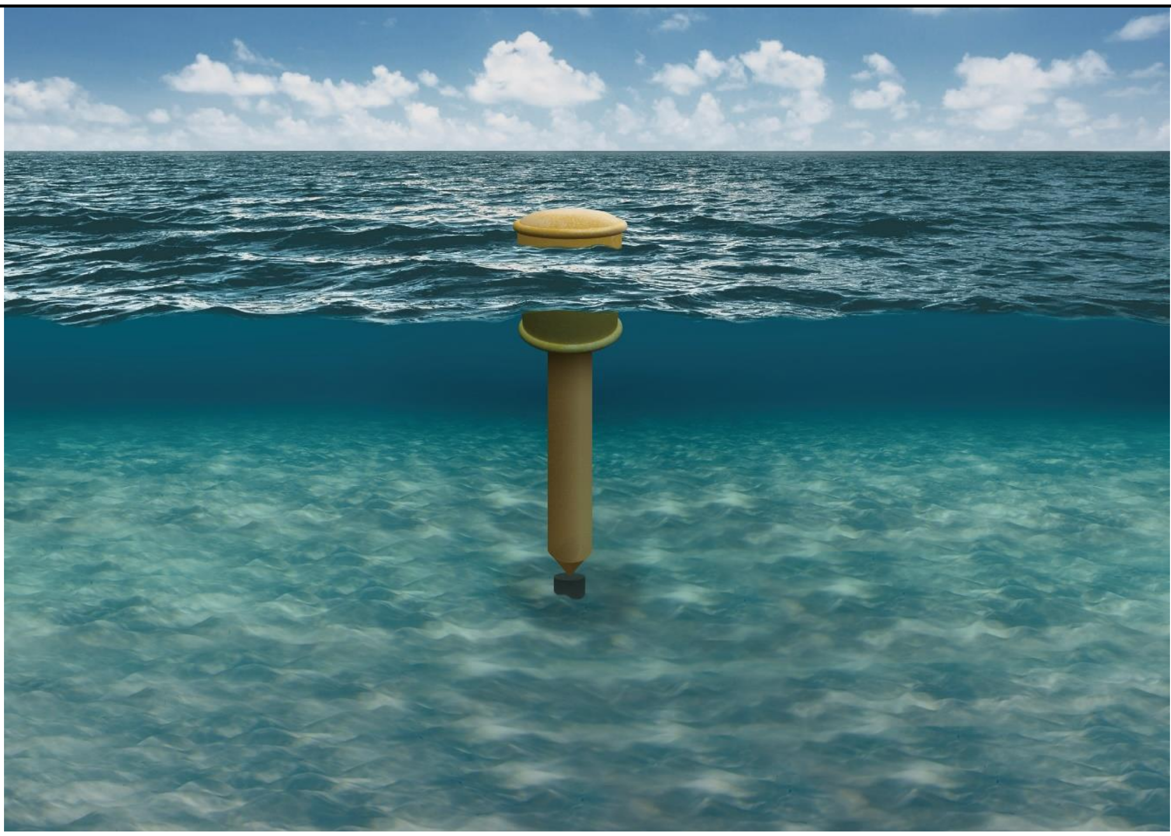
3.2.6 #6 Multi-Tether "Admiralty" Type Mooring

#6 Multi-Tether "Admiralty" Type Mooring

Description: This system is an adaption of the commonly used Admiralty mooring for vessels in coastal waters. Its popularity is thanks to excellent compliance characteristics which mean it is functional in shallow waters with high tidal range and gives good survivability in aggressive sea states. The footprint is relatively small and the use of drag embedment anchors is allowed owing to the clump weights and chains to anchors. The compliance also means component MBLs are minimised thus improving the CAPEX of the system. This may be an attractive solution allowing the use of drag embedment anchors in shallower waters where sufficient stable sediment exists. However, it is a complex system with many connections, and since failures commonly occur at discontinuities in mooring systems, this is likely to be an unreliable system.
Advantages: • A very compliant mooring system that should achieve a workable design with lower strength components. • Very compact footprint (anchor radius) which is a lot smaller than a multi-leg chain mooring. • Uses DEAs which have a lower cost than VLAs. • Synthetic ropes can be used for vertical tether lines (either polyester or nylon) to increase compliance and reduce overall cost. • Has the benefits of TLP, but able to provide some heave compliance in survival conditions.
Disadvantages • Require sinker weight(s) to pre-tension the vertical tethers, which have to be supported by the buoyancy of the WEC device. • Large excursions may be an issue (e.g. in respect of power export cables etc.). • Large lengths of chain may be required on the seabed to avoid uplift at anchor. • There are a large number of discontinuities in the system which increase the risk of system failure • Unlikely to be as compliant as system category #2 synthetic mooring in shallower wave exposed environments. •Associated installation complexity.
Key failure modes/risks: • Sinker bar can bounce off of seabed and swing about causing risk of failure to associated components. • Lots of lines and connections with the associated risk of failure

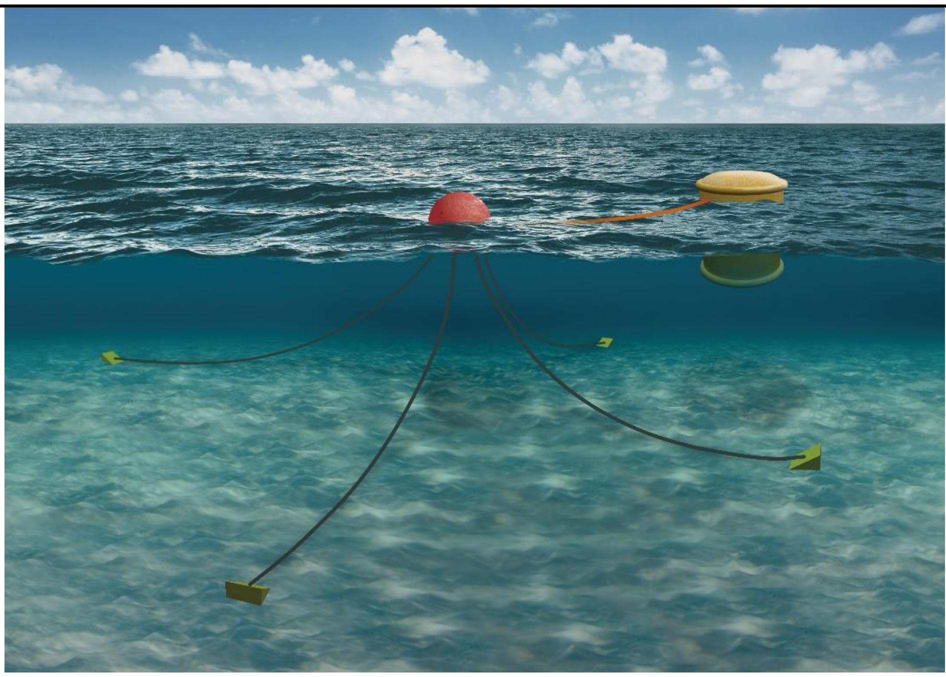
3.2.7 #7 Single Leg Tension Mooring

#7 Single Leg Tension mooring

Description: There is a class of surface and submerged point absorbers which operate using a single tether with integrated in-line power take-off, which is ground referenced. The PTO and any tidal compensation equipment could be housed within the device, at the anchor end or possibly mid-line. Normally suited to intermediate water depths in the range of 40m to 50m. It may be possible to go shallower or deeper, depending on technology, scale and wave regime.
Advantages: • PTO and mooring system are integrated. • Small footprint
Disadvantages: • Susceptible to snatch loads in shallower water. • No redundancy should a mooring component fail (requires a high factor of safety for non-redundant systems). • May have a requirement for tidal compensation •Large vertical anchor loads • Challenging to install with large pretension in the system.
Key failure modes/risks: No redundancy built into the system.

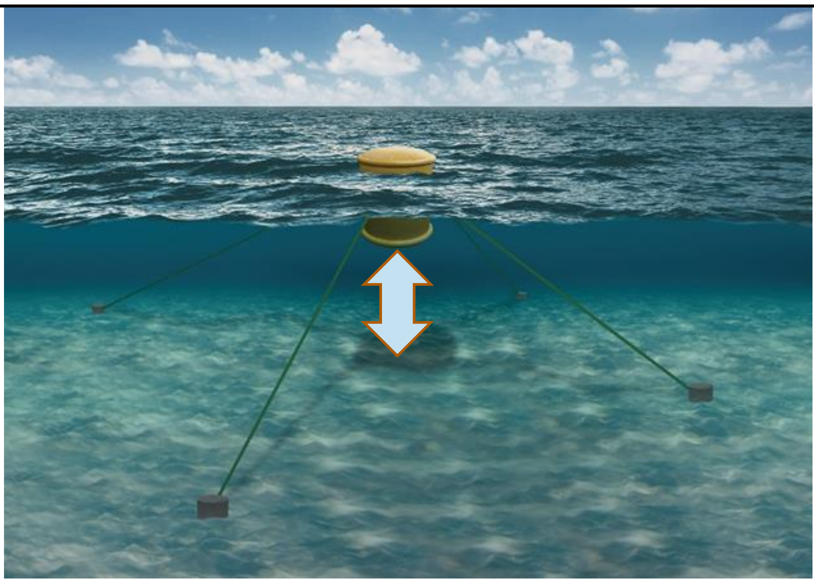
3.2.8 #8 Articulated Tower

#8 Articulated Tower

Description: A variation on category #7, some devices may adopt rigid leg or jacket which can accept compression loads, although could still be classed as a compliant mooring if they have a universal joint (for instance at seabed to allow pitch compliance and possible load reduction, compared to fixed device). There is evidence that increasing the effective density of the tower close to the density of seawater can result in long pitch resonance periods which can significantly reduce horizontal loads albeit at the expense of large pitch angles.
Advantages: • Small footprint. • Tends to be used to avoid snatch loads. • Some evidence shows that foundations loads can be lower compared to an equivalent fixed structure.
Disadvantages: • Benefits may be very device specific. • Large pitch angles are a compromise for low foundation loads. • No redundancy
Key failure modes/risks: Wear at the universal joint, column buckling and plastic deformation on overload.

3.2.9 #9 Single Point Mooring

#9 Single Point Mooring

Description: Single point mooring (SPM) systems normally comprises a spread mooring (equivalent to categories #1 to #3) which connects to a single buoy which could be at the surface or submerged. The WEC is then linked to this intermediate buoy via a horizontal hawser which may be rigid or flexible
Advantages: • Depending on the key operating mode the WEC is relatively decoupled from the main mooring system in heave, pitch, roll and sway and less so in surge. • One key feature is the yaw compliance which gives the potential for the WEC to weathervane in operating and or survival waves (i.e. may be more suitable for directionally sensitive devices).
Disadvantages: • For a non-redundant system, the hawser would normally be required to adopt high factor of safety for the line, although there are options to build in redundancy. • The WEC may be exposed to oblique current or wind loads or bi-directional seas which cause misalignment of the WEC with waves thus necessitating some form of active yaw control (e.g. tail mooing on winch) to achieve optimal weathervaning. • The intermediate buoy could end up being quite large and in itself attract hydrodynamic loads. • The requirement to keep hawser under sufficient load to prevent flex fatigue (traditional SPM hawsers can suffer from this and typically they only last 1-2 years). Note the Pelamis Wave Power quick connect mooring system (which acts a bit like a submerged SPM) avoids this by using a rigid connection to the submerged buoy.
Key failure modes/risks: Hawser life can be affected by: i) surface and internal wear, ii) tension-tension fatigue iii) flex fatigue, iv) axial compression fatigue, v) creep and vi) hysteresis heating.

3.2.10 #10 Active Submergence

#10 Active Submergence

Description: Some WECs adjust their height in the water column depending on the sea state (e.g. winch down in survival conditions to reduce loads on the mooring system). Need to be sufficiently deep, so that water particles velocities and acceleration are not significant at a position lowered to in the water column.
Advantages: •Avoidance of largest wave loads and impact waves.
Disadvantages: • May require "failsafe" mode to ensure the system is not stuck at the surface in survival conditions. • Winching mechanisms could be vulnerable to wear and damage through repeated winch cycling and need to be properly qualified and tested at an intermediate scale.
Key failure modes/risks: • Winching mechanisms and control may be vulnerable to water ingress, marine fouling and in the case of winch lines bend-over-sheave fatigue.

3.2.11 Common Risks

The following risks are common to the ten mooring system categories introduced above:

- Premature component failures due to wear, overloading, fatigue, unexpected failure modes and/or line discontinuities.
- Corrosion of steel components (chains, wire ropes or connecting hardware).
- Snatch loading leading to component fatigue or overloading.
- Design loads potentially over- or underestimated due to current limitations of modelling these materials, components or subsystems.
- Unexpected vortex induced vibration (VIV) of taut lines.

3.3 Mooring Line Components and Materials

3.3.1 Overview

Traditionally offshore mooring systems in exposed locations (e.g. for permanent moorings or O&G drilling activities) have tended to adopt steel-based mooring components, such as chain and/or wire ropes. Historically synthetic ropes have been associated with temporary moorings such as the shipping and ports industries where ropes can be easily inspected and replaced. While there has been a degree of conservatism in the uptake of new materials in the O&G industry, the Brazilian petroleum industry saw an opportunity to develop a polyester-based mooring system for the exploitation of deep-water sites in the 1980s. Polyester was identified as game-changing compared to conventional steel-based moorings mainly due to lighter weights, line loads and lower costs for a given MBL. Polyester was also a benefit to the riser system with improved station-keeping, smaller installation vessels (and hence lower installation cost compared to steel-based systems) and finally smaller anchor radii. The weight saving also reduces the amount of structural buoyancy required to support the mooring system in deepwater. For one deepwater spar project, the hull steel weight saving was 13% [2]. Since the 1980s there has been a significant development in synthetic mooring line materials, rope constructions and manufacturing techniques for a wide range of mooring applications.

In the context of WECs, the desired material and rope characteristics will very much depend on the given application. For spread moored systems there tends to be a requirement for mooring compliance in survival storms to reduce both mooring and anchor loads. A reduction in line loads is likely to correlate with a reduction of loads transferred to the device structure. Research into floating production, storage and offloading (FPSO) vessel structural loads has indicated that mooring loads can affect longitudinal bending modes (known as 'hogging' and 'sagging') [3]. An alternative to catenary based compliance is the adoption of ropes or components with relatively high axial compliance. Nylon has excellent compliance properties and has historically been used for temporary moorings in the marine and shipping industries. Nylon has been used very successfully in permanent wave exposed marina pontoon and breakwater mooring applications for the last 12 years. In a recent storm which destroyed Holyhead marina[7], many chains failed, but not one single nylon rope broke after 10 years service. Furthermore, nylon samples used in this mooring still had 80-90% residual strength despite regularly being in contact with the seabed. However conventional braided constructions had relatively poor fatigue properties. With major improvements with fibre coatings over the last 5 - 10 years, some braided construction might be applicable. These ropes are still generally not deemed suitable for

[7] 'Storm Emma smashes boats at Holyhead marina, Anglesey' https://www.bbc.co.uk/news/uk-wales-north-west-wales-43257319 [Accessed online: 01/05/2018].

permanent moorings as they require regular inspection and replacement. However, these requirements may change in light of recent findings on marina moorings with long-term usage. In the last 20 years, rope manufacturers have developed, tested and qualified new rope constructions (e.g. parallel strand) which exhibit superior fatigue resistance, even in comparison to steel-based moorings. Unlike steel-based components synthetic ropes and elastomers tend to have a non-linear, time and load dependent stiffness properties. Changes in the compliance of these materials are possible over the lifetime of the component and should be factored into the design of the mooring system. Relevant procedures for the design and usage of mooring system components include DNVGL-OS-E301 Position Mooring [4], DNVGL-OS-E302 Offshore Mooring Chain [5], DNV-OS-E304 Offshore Mooring Steel Wire Ropes [6] and DNV-OS-E303 Offshore Fibre Ropes [7]. Although offshore standards exist for the design, testing and usage of synthetic ropes, these standards do not explicitly address the complex behaviour demonstrated by these materials which is important for mooring design and analysis. As will be discussed in Section 3.10.2 this is an on-going activity by both classification societies and R&D groups.

An alternative to synthetic-based ropes are elastomeric shock absorbers. There are also concepts for hose pump-type technology which can also be used to absorb power, while providing compliance. Examples of mooring shock absorbers are described in more detail in Section 3.4.1. These are generally at low technology readiness levels (TRLs). Current state-of-the-art for elastomeric solutions tend to have a break load range up to 400T. Whereas nylon and polyester ropes are commercially available in the range of up to 1000T-2000T break load. DNV-GL have conducted break load tests on one of the world's largest fibre ropes for mooring of deep water installations (2900T).

Incidences of riser fatigue in the O&G sector were attributed to too stiff mooring systems causing riser touchdown in the same position which led to fatigue concentrations in one position. Although WECs tend not to have riser-type equipment between the device and seabed, parallels could be drawn with concerns of fatigue concentrations occurring to the export power cable either at the touchdown point, at the WEC entry point or midwater arch (if relevant). Use of a compliant mooring system (through system geometry and/or structural properties of the line) is likely to distribute bending and touch down fatigue along the length of the power cable rather than one point. Of course, excessive compliance tends to increase device excursions, which can make the export of power via umbilical cable more challenging. Equally, compliance can impact on power capture performance. For example, ground-referencing or tension leg platform type systems may require high modulus materials and rope constructions.

The following sections consider these materials in more detail. Less consideration is given to conventional materials such as wire and chain as this is well understood and reported elsewhere (e.g. [8, 5]). However, where appropriate the properties and characteristics of steel-based components are included for comparative purposes.

3.3.2 Metallic Components

Metallic components typically used in mooring lines include wire ropes, chains and connecting hardware (shackles, links or connectors and swivels) and also clump weights (e.g. Figure 4). For example, chains have widespread use for a number of reasons including: i) a track record of usage offshore and corresponding acceptance by classification societies, ii) high availability, iii) zero bend stiffness, iv) high mass per unit length (which can be utilised to reduce vertical anchor loads in the case of ground chain), v) well-understood mechanical properties for modelling (e.g. constant axial stiffness) and vi) no pre-stretch installation requirements (i.e. zero creep).

Figure 4: Examples of metallic mooring components: (left) Mooring chain (source: www.pexels.com), (centre) wire rope (source: www.pexels.com) and (right) Steel connector with 1700T break load polyester rope (source: TTI)

For offshore mooring chains, six commonly used tensile strength grades include: R3, R3S, R4, R4S, R5 and ORQ (oil rig quality). Certification guidance covering the design, manufacture, testing, usage and decommissioning of chains can be found in several standards including those produced by the American Bureau of Shipping (ABS, e.g. [8]) and Det Norske Veritas Germanischer Lloyd (DNVGL, e.g. [5]). Table 3 provides examples of proof and break loads for several bar diameters of studlink chain. A comparison of catenary systems using two grades was conducted in the Mooring and Foundation Case Studies reported in Section 6.

Table 3: Comparative strengths of three different offshore chain grades for selected diameters (source: Sotra).

Diameter [mm]	Proof load [kN]			Break load [kN]		
	ORQ	R3	R4	ORQ	R3	R4
20.5	249.0	263.0	385.0	376.0	397.0	488.0
50.0	1400.0	1480.0	2160.0	2110.0	2230.0	2740.0
81.0	3446.0	3643.0	5317.0	5194.0	5490.0	6745.0
111.0	6058.0	6404.0	9347.0	9130.0	9650.0	11856.0
137.0	8682.0	9178.0	13395.0	13085.0	13829.0	16992.0

Wire rope is also used for offshore moorings and guidance covering the design, manufacture, testing, usage and decommissioning offshore can be found in certification standards (e.g. DNV-OS-E304 [6]).

Component testing procedures for steel components are summarised in Section 3.9.2 with considerations for component durability and reliability introduced in Section 3.3.4. To overcome problems with carbon steel fatigue, connectors have been designed using super duplex stainless steel plates and pins, with low friction spools to connect synthetic fibre ropes. However, these are still heavy, expensive and difficult to assemble.

3.3.3 Synthetic Ropes

Synthetic ropes have become an accepted alternative to chain and steel wire rope mooring lines in recent years. A variety of materials feature in commercially available synthetic ropes with the most likely applied to the WEC sector being:

- Nylon (polyamide, PA)
- Polyester (PET, PEN)
- Aramid

- High modulus polyethylene (HMPE)
- Liquid-crystal polymer (LCP)

Polyester is currently the most widely used synthetic material for permanent mooring systems.

The strength per unit weight of these four materials is significantly higher than steel. The low weight per unit length means that they are significantly easier to handle and therefore install. Low-modulus synthetic materials stretch to a greater level than steel before failure and it is this compliance which is one of the main advantages of using these materials in mooring ropes, especially where geometric compliance is limited in a mooring setup, e.g. shallow water. For example, steel lines on 16 mobile offshore drilling unit (MODU) failed in the Gulf of Mexico during Hurricanes Ivan (2004), Katrina (2005) and Rita (2005) causing the platforms to drift [9]. Not one single polyester line failed during these incidents.

For taut-moored applications requiring ropes with a tensile strength which is comparable to steel but with a considerably lower submerged weight, high modulus-high tenacity materials (HM-HT) such as high modulus polyethylene (HMPE), liquid crystal polymer (LCP, e.g. Vectran®) and aramid can be used.

Nylon was originally regarded as useful only for temporary moorings due to poor fatigue life. However, thanks to new rope designs, yarn marine grade lubricant and recent development programmes, nylon fatigue life has been increased. For example Ridge in [10] demonstrated that wet nylon subropes subjected to 20,000,000 load cycles had a residual strength level of 108% (based on average new breaking strength).

Case study – FLOATGEN floating wind turbine

Offshore floating wind developer IDEOL was a partner on the Scottish funded Marine Renewables Commercialisation Fund (MRCF) project into moorings and anchors led by TTI [11]. As part of this project, IDEOL provided a comparison of the benefits of chain, polyester and nylon synthetic rope-based moorings for their FLOATGEN prototype which was deployed at the SEMREV site this year (2018) on French Atlantic coast. The displacement of the FLOATGEN is ~6000T and it was moored in a water depth of 32m with an extreme design significant wave height of 9m. The challenge for IDEOL was that they had to design a mooring to fit within the confines of the consented berth. Their assessment showed that nylon was the most viable and cost-effective solution. The peak line tensions for the nylon mooring legs (~3500kN) were found to be 30% to 50% lower than other options considered. The nylon based system achieved a hardware cost which was 20% lower than the polyester solution and less than half the price of an all-chain system. The installation time of the semi-taut leg system (both polyester and nylon) was estimated to be 17% lower than for the chain system. While significant work was conducted into the qualification of nylon rope with MRCF partners Lloyd's Register[8] there are areas in nylon qualification which need to be addressed (see below). Qualification steps are being addressed as part of the FLOATGEN offshore deployment with the aim of achieving a fully qualified rope. The project also concluded that in the future there are also opportunities for further innovation in synthetic rope design.

Nylon ropes can now be considered for permanent MRE mooring systems as they have the advantage of superior compliance which is important for the WEC market. The next logical stage in adopting these components widely is certification, either to an existing standard or the development of a new standard by a certification agency. This would provide the necessary legal and formal confidence in

[8] The Maritime Executive, "Industry Project Looks at Windfarm Mooring Lines" http://www.maritime-executive.com/article/industry-project-looks-at-windfarm-mooring-lines [Accessed 15 05 2018].

the product for its end users as well as appropriately scrutinising the product on a technical level. Efforts have been made in applying existing certification guidance to nylon ropes, for example, the latest version of DNVGL-OS-E303 [7] released in 2016 now mentions nylon as a 'load-bearing yarn material'. Despite this progress, current challenges for the sector which warrant further collaboration and research include:

- No approved supplier of nylon yarn currently exists worldwide (for example approval to DNV TAP 322)
- Current guidance may not be the best fit, commercially or technically, for the MRE sector, for example, the scope and extent of the '3-T' (tension, time and temperature) approach to testing [7] (see Section 3.9.3)
- Concern (from rope manufacturers and developers) about the costs associated with extensive testing and certification. These costs would be easily absorbed by rope orders for the first large commercial WEC farms.
- Larger scale commercial WECs and other MRE systems are expected to require lines which have an MBL well in excess of 1000T. The impact of this on testing, qualification and certification requirements should be explored.

Behaviour

Synthetic rope responses are dependent on the applied mean load and load range and crucially previous loading history [12, 13]. Loading rate is generally not important except for the first few load cycles in the rope life and therefore response sensitivity to loading rate is negligible at the load frequencies of interest for mooring systems. All synthetic ropes absorb and dissipate energy during dynamic loading which can reduce the magnitude of peak loads. This is due to the viscoelastic or hysteretic response of these materials and results in different 'loading' and 'unloading' stiffness curves caused by a delay in strain response[9]. The energy dissipated (typically as heat) is the area between loading and unloading curves on the load-extension diagram.

Higher modulus materials such as HMPE are susceptible to creep and this behaviour requires careful assessment as part of the design process for mooring lines featuring these materials. Although predictable, long-term creep may necessitate re-tensioning of the lines, to avoid a drop in quasi-static stiffness of the mooring system particularly during prolonged storm conditions. Depending on the material re-tensioning may be required on an occasional basis (i.e. 1-3 times during say 25 year life). Primary creep, occurring at low-stress levels recovers (immediately or after a delay) when the applied load is close to zero. However, secondary creep which takes place at higher stresses is not recoverable. The rate of creep increases with increasing specific load and temperature and can (in the case of secondary creep) ultimately lead to failure of a mooring line. Creep need not be a serious problem if it is properly accounted for in the design of a mooring line (e.g. shallow water temperatures at certain latitudes) and indeed notable developments to improve the creep performance of ropes have taken place.

To give some data to the above descriptions, Figure 5 shows specific stress-elongation curves for the different synthetic materials (as fibres) and steel. As shown, HPPE (HMPE) and aramid are the 'stiff' synthetics and polyester and nylon the 'compliant' ones. Clearly all have an elongation to break significantly greater than steel. Table 4 gives material densities, moduli, tenacity and break extension and this demonstrates that all of the synthetic materials considered have greater tenacities than steel,

[9]The relationship between stress and strain is time-dependent for viscoelastic materials and is characterised by the absorption and dissipation of energy during loading and unloading (hysteresis). Whilst viscoelastic deformations are recoverable, viscoplastic behaviour manifests as rate dependent unrecoverable deformation.

increased break extensions and are significantly lighter. To provide a tangible comparison of the influence of material choice, a selection of rope characteristics for 12 strand ropes with an MBL around 400T are listed in Table 5.

Figure 6 shows a typical rope or sub-rope test whereby a new rope is cycled 10 times to ~50% MBL and then to failure on the 11th cycle. As shown the first and second loading cycles impart a permanent elongation to the rope which then stabilises with continued loading. The load-unload hysteresis loops during cycling are also apparent.

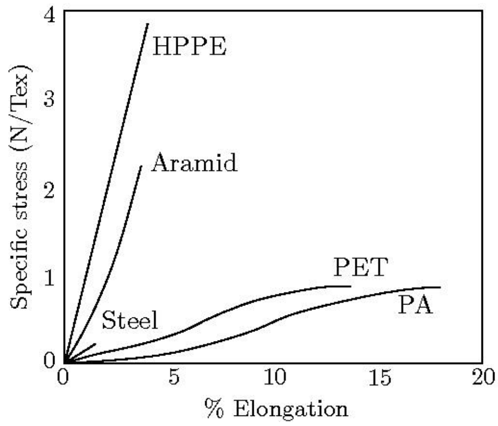


Figure 5: Specific stress-elongation curves for synthetic materials and steel (reproduced from [14]. Note: Tex is a linear mass density of fibres that has units of g/km.

Table 4: Selected material properties (reproduced from [15])

	Nylon 6	**Polyester**	**Vectran® HT**	**Aramid**	**HMPE**	**Steel**
Density (g/cmˆ3)	1.14	1.38	1.4	1.45	0.97	7.85
Melting point (°C)	218	258	400 (chars)	500 (decomposes)	150	1600
Modulus (N/tex)	7	11	54	60	100	20
Tenacity (mN/tex)	840	820	2286	2000	3500	330
Break extension (%)	20	12	3.8	3.5	3.5	2 (yield point)
Moisture (%)	5	<1	<0.1	1–7	0	0

Table 5: Material comparison for 12 strand ropes with a ~400T MBL. The listed fatigue life values are for a load range of 0-100tf. Axial stiffness (EA) values are listed for load levels 20/40/100tf (tonnes-force). Non-recoverable creep elongation is based on 5 years at a constant load of 100tf.

Material	Grade	Dia (mm)	Mass (kg/m)	Spliced MBL (tf)	Fatigue Life (Cycles)	EA (tf)	Creep Life (Years)	Creep Elongation (%)
HMPE	SK75	80	3.57	411	>1 x 10^8	12100/ 16300/ 16000	>50	4
	SK78						>50	3
Co-Polymer Aramid	Technora	84	5.62	424	>1 x 10^{10}	7300/ 10100/ 16800	>50	1
Aramid	Twaron/ Kevlar	84	5.39	404		8000/ 11000/ 18500	>50	1
LCP	Vectran	80	4.89	428	>5 x 10^6	8200/ 11000/ 20600	>50	1
Polyester	Generic	128	14.47	411	>2 x 10^7	3000/ 3600/ 5800	>50	1

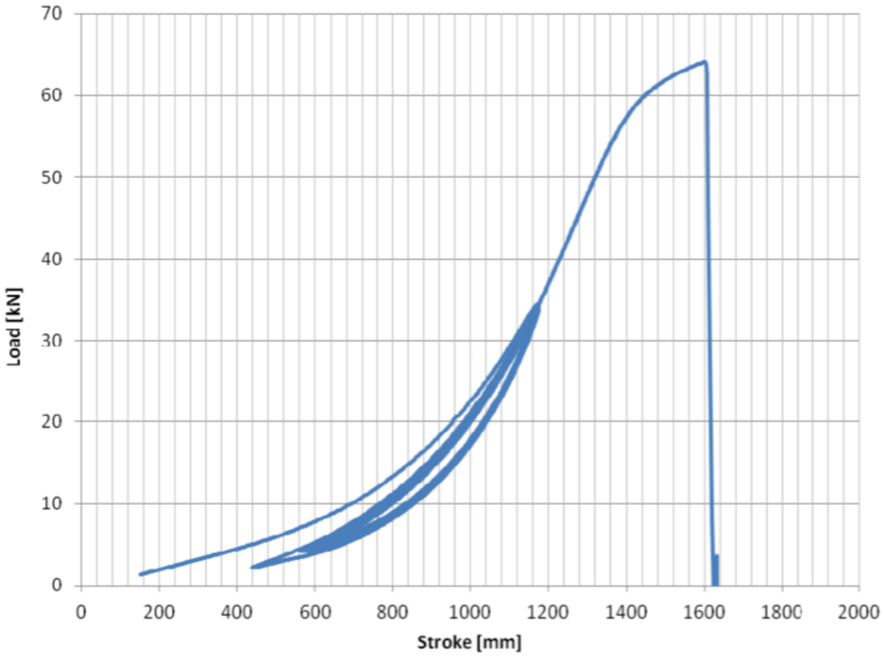


Figure 6: Nylon subrope subject to 10x sinusoidal load cycles followed by load-to-failure (source: TTI).

Rope Constructions

Most commercially available rope constructions are 'hierarchical' – starting from individual fibres (with diameters ranging from 10 - 50µm) which are twisted to form yarns, yarn assemblies and strands as shown in Figure 7 for a standard or typical 3-strand laid, twisted construction. Parallel stranded ropes are also available and tend to be used for high load applications. They comprise strands assembled into sub-ropes which are arranged in a parallel fashion and contained and protected by a braided jacket.

Figure 8 shows a typical construction of such a rope. Braided and plaited constructions are also available (e.g. Figure 9).

In addition to the material properties, rope construction also influences rope performance. Figure 6 shows the response of the rope following initial loading is different for subsequent cycles. The resulting permanent elongation is partly due to the visco-plastic strain of the material as well as rearrangement of the rope structure.

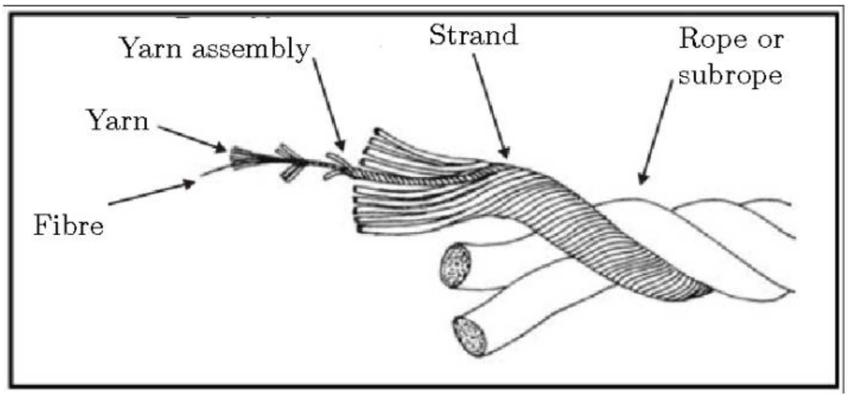


Figure 7: Typical hierarchical rope construction [16].

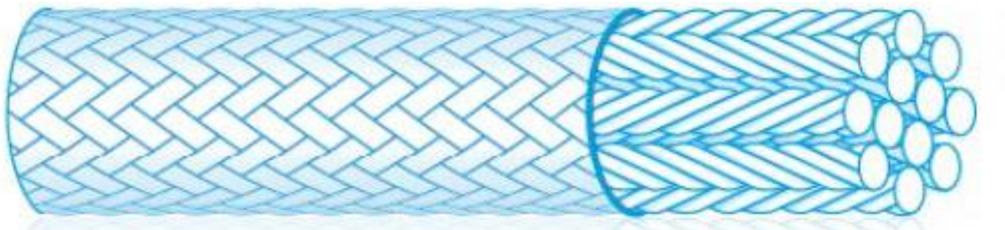


Figure 8: Parallel strand rope structure (source: BEXCO©)

Figure 9: 12-strand braided rope construction (source: BEXCO©)

3.3.4 SYSTEM RELIABILITY AND COMPONENT DEGRADATION

BACKGROUND

Within the offshore sector significant progress has been made to understanding the mechanisms of component failure and this has led to the development of appropriate design codes and better manufacturing processes. Despite the overall reduction in failures of offshore platform mooring lines (around 0.5 per annum for MODU mooring lines and 0.2 per annum for FPSO unit lines) failures still occur due to a variety of causes [17].

A comprehensive study was conducted recently by Ma et al. [18] on mooring line failures in permanent oil and gas production platforms. During the period 2001-2011 nine reported system failures occurred in around 300 moorings. However, a failure is defined as a breakage to two or more mooring lines or an incident resulting in riser damage. Given the redundancy provided in oil and gas moorings single-line failure cases are not deemed incidents but a further 31 of these cases were also examined. This is more pertinent for WECs as the redundancy in the system is likely to be lower.

Some of the learnings established are summarised as:

- The majority of the failures occurred at or near the line fairleads
- Some failures could have been prevented through more robust inspection and monitoring
- Some were due to newly discovered phenomena such as out of plane bending in chain
- In the majority of instances, failures occur at an interface or discontinuity
- Chain and wire rope in contact with the seabed was a common issue
- Corrosion had been a major contributor to several incidents
- It is more cost effective to build redundancy or margin in a new design during the CAPEX phase compared to carrying out a mooring repair or replacement in the future
- Inspection of wire or chain seems not to have identified incipient failure modes (see second point above)
- One synthetic rope failure was reported (the Girassol FPSO), the cause of which was previous damage sustained by a steel wire rope used during an ROV inspection. Therefore it could be argued that this is not a genuine failure case[10].

The authors are not aware of a centralised database which includes mooring and anchoring components (i.e. not even in the offshore and onshore reliability data (OREDA) Handbook [19]). Other reviews have been conducted (e.g. [20, 21]) but these tend to be limited in terms of providing failure statistics or are specific to one particular platform or vessel type. The review conducted by Ma et al. in [18] concluded that based on mooring system failures reported between 2001 and 2011 the annual probability of multiple line failure is in the order of $3x10^{-3}$. The following failure mechanisms were identified in a review conducted by DNV-GL [22]; fatigue (in particular tension-tension fatigue[11] of chains in addition to out-of-plane bending and torsion induced fatigue), wear, corrosion, overloading, manufacturing defects, damage during installation and operation and also under-design.

Details of the failure incidents are typically sparse or incomplete and often failures go unreported (i.e. due to ignored, faulty or non-existent alarms, see Section 3.8.4). Therefore it can be reasonably assumed that over the period analysed many more failures occurred globally than those which have been reported. Non-permanent platforms such as MODUs are often used in several locations perhaps with the pre-emptive replacement of mooring system components during each deployment, and

[10] This incident is of interest because 3 or more chains failed all within one month, whereas all of the polyester ropes survived with 100% residual properties (the testing was conducted by TTI).
[11] Tension-tension fatigue testing involves the application of loads greater than zero (i.e. no compression).

hence the life of the mooring parts that have failed may not align with the duration of the installation. To provide some measure of reliability, TTI has compiled a database of reported failures of mooring components used in oil and gas production and non-production mooring systems. From this annual failure rates have been derived of 2.62 x 10^{-4} failures/annum and 1.16 x 10^{-4} failures/annum for chain and synthetic rope respectively[12]. The number of reported anchor failures is too low to derive meaningful failure statistics, and for this reason, a target level of 1.0 x 10^{-4} failures/annum is used, corresponding to the Recommended Practice of the American Petroleum Institute guidelines [23].

It is clear that even with long-standing research, extensive design and engineering, the failure rate is still much higher than the offshore industry expects for steel components in mooring systems. Fundamentally it is not currently possible to obtain failure rates for MRE mooring and foundation components or subsystems due to: i) concerns over commercial confidentially and ii) a lack of design convergence and iii) the lack of long-term deployments required to derive meaningful failure rate statistics. Hence there is a need to consolidate mooring and foundation failure reporting and data collection across both the offshore and MRE sectors, for example the dissemination of environmental measurements, WEC motions and mooring load data as part of the H2020 Open Sea Operating Experience to Reduce Wave Energy Cost (OPERA) project [24]. As with the offshore O&G industry the partial or full failure of a WEC mooring system has to be reported to the Health and Safety Executive in accordance with the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR), in addition to monitoring requirements [25]. Whilst no specific guidance for WECs is available from the Maritime Coastguard Agency (MCA) and Marine Accident Investigation Board (MAIB), these organisations would also have to be informed in the event of a mooring failure.

The loading regimes experienced by WEC mooring systems are likely to be the result of energetic environmental loading and hence careful design and analysis is required to avoid fatigue degradation and failures. This is more of an issue for steel components in the system but the synthetic fatigue performance must of course also be understood. Section 3.9 introduces testing procedures.

SYNTHETIC ROPES

Potential degradation mechanisms for synthetic fibre ropes include:

- Tension and/or compression fatigue
- Particulate ingress and abrasion
- Creep
- Hysteresis heating
- UV exposure
- Wet/dry cycling
- Snatch loading leading to heating and/or overload
- Damage during handling or installation

Tension-tension fatigue is the damage caused by friction occurring between adjacent fibres which are subjected to repeated cycling. Because this can be accelerated by the ingress of foreign particulates into the rope structure, filtration screens are often used throughout whole rope length including the eyes and splices. Fibre ropes have very low variation in fatigue life and through-life properties. After years of deployment experience and laboratory testing the offshore industry has come to the

[12] The failure rates are derived from reported failures. The records assume an estimated 1770 offshore units with mooring systems featuring chain deployed over a 35 year period and 230 units with mooring systems featuring polyester rope deployed over a 15 year period. They represent an estimation of the probability of failure of a single line, assuming 8x lines per MODU and 12x lines per production rig.

consensus that polyester ropes have superior fatigue characteristics when compared to other commonly adopted steel components such as chain, shackles, H-links and spiral-strand wire ropes. Tension-tension fatigue tests have demonstrated that polyester has at least 50x longer fatigue life than steel wire rope [4] with very low coefficients of variance in fatigue performance [26] and as such fatigue life shouldn't be an issue for well-designed polyester fibre moorings. The tests conducted by Ridge et al. in [27] also showed very low variation in fatigue life for nylon. As a result of recent research and development, nylon fatigue life has been increased to such an extent that it can also be used for permanent mooring systems (e.g. [10]). Low variance in fatigue life is important and useful as it provides high-certainty fatigue analysis and therefore allows the capacity of the rope to be utilised more efficiently. In other words, a fatigue safety factor which is lower than for other materials with high variance could potentially be utilised. This would require certification codes to be further developed though.

As mentioned in Section 3.3.3 stiffer materials such as HMPE have a tendency to creep. Factors affecting HMPE creep behaviour are fibre type, applied load, load duration, and temperature. Recent development in new grades of HMPE have led to improved creep properties in both reduced strain and increased rupture life, so it is vital to specify the applicable fibre grade to the application and to seek specialist advice.

Stiffer materials such as aramid and to a much lesser extent HMPE are also susceptible to axial compression fatigue, where fibres buckle under low loads and become concentrations for fatigue damage under cyclic loading. As such, it is important to avoid the rope becoming slack and going into compression and this necessitates significant pretension in the mooring system, or alternatively designing the system to reduce the number of low tension cycles.

Under dynamic loading (generally large load ranges which only occur in severe storms) it is possible for significant temperature increases to occur from hysteresis heating. In extreme cases of localised heating this can result in melting or peeling of fibres. While this phenomenon was once of concern for large diameter polyester ropes used on offshore platforms [28], the issue has not materialised during the 20 years of use in the sector. However hysteresis heating may be an issue for smaller, more dynamically responsive equipment such as WECs. Snatch loading, particularly when part of the mooring system is temporarily slack (such as the leeward lines) may also result in hysteresis heating (if load ranges are high) or overload.

Protective coatings such as woven jackets or polyurethane coatings reduce the likelihood of damage to load-bearing components during handling or installation. That said, offshore operators Aker and Statoil in Norway have extensively used 800T polyester ropes on standard anchor handling vessels (AHVs) designed for wire and chain systems with no modifications made for 2-3 years and conducted work-over and MODU preset moorings for 50 operations and found no significant jacket damage. Of course the steel deck equipment must be free of grooves and not corroded which could lead to abrasion. As a precautionary measure it is important that safe working practices are adopted during use and installation. Furthermore Petrobras bans use of wire work ropes anywhere near a synthetic mooring. Furthermore attempts have been made to monitor rope integrity in-service to alert the user to impending failure (see Section 3.8).

CHAIN AND CONNECTING HARDWARE

Potential degradation mechanisms for chains and connecting hardware include:

- Tension, out-of-plane bending and torsion fatigue
- Wear

- Corrosion
- Overload
- Manufacturing defects
- Damage during handling or installation
- Incorrect or inappropriate repair procedures
- Hydrogen embrittlement (HE) and hydrogen assisted cracking (HAC)

Figure 10 identifies locations and type of typical failures for chain based mooring systems. Chain is particularly vulnerable to damage in the “thrash zone” (repeated and cyclic contact with the seabed) or "splash zone” (contact near the fairlead), resulting in high stresses in the chain links and exacerbated wear. The impact of thrashing also depends on seabed type (i.e. these components are particularly susceptible to impact with hard rocky seabeds) and hang-off geometry at the fairlead. Corrosion rates can vary along the length of the line. For example if regular remotely operated vehicle (ROV) inspections take place rates of corrosion allowance are high near the splash and thrash zones (0.4mm/year) and lower along the rest of the catenary (0.3mm/year) [4]. In addition sacrificial cathodic protection is usually provided to reduce corrosion rates (e.g. hot-dip galvanisation of steel chains) [29]. Studded chain may also be more prone to corrosion in the thrash zone. As studs can become loose enough to move freely, the rate and magnitude of corrosion (e.g. Figure 11) is magnified, due to the fretting of surfaces, which may also lead to crevice corrosion in the early stages. The fairlead connection point is also particularly vulnerable. This tends to be the location where highest line tensions are recorded and where chain out of plane bending can occur (Figure 11).

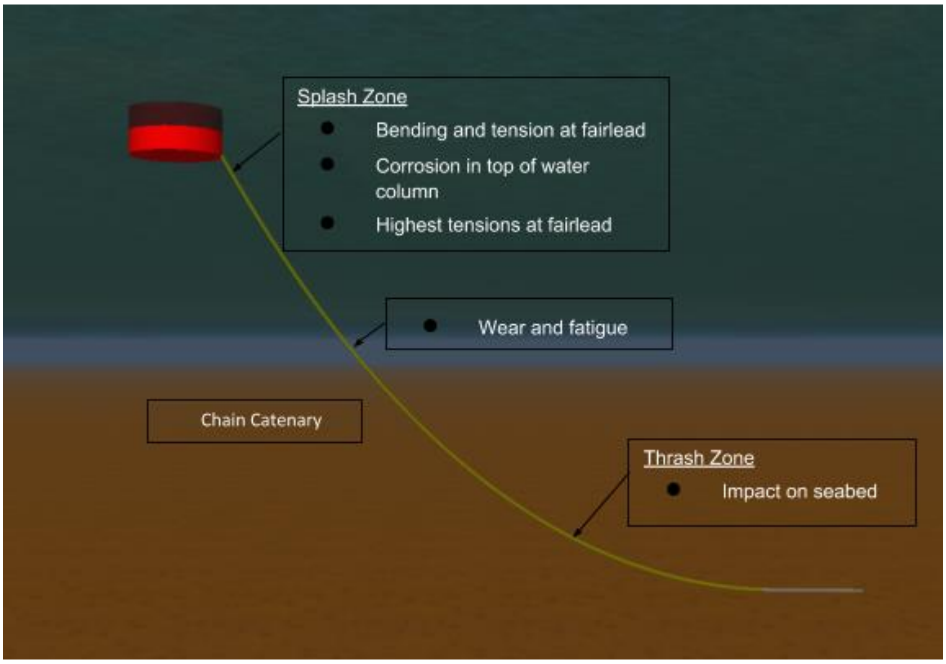
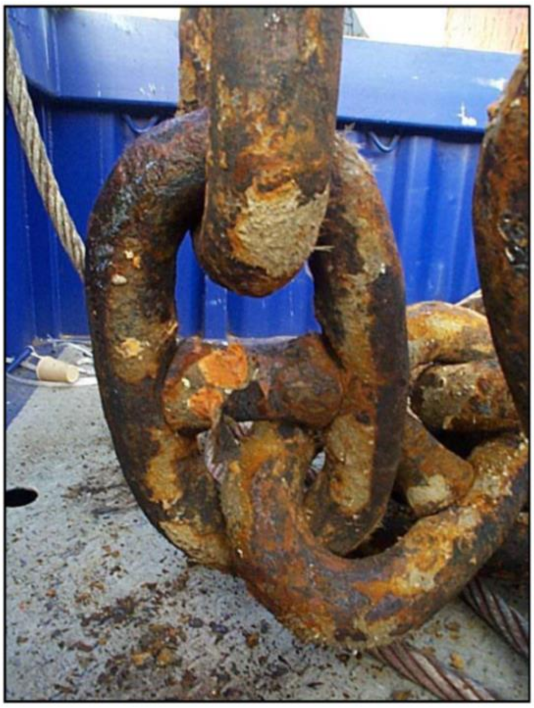


Figure 10: Key locations of potential chain failure for a chain catenary system (source: TTI)



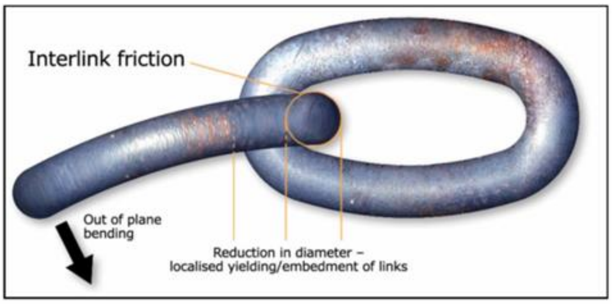


Figure 11: (left) Example of corrosion on floating production system after 16-years of service [17] (right) Chain out of plane bending [30].

In addition to the degradation mechanisms introduced, Gordon et al. in [22] reports on other potential failure modes including; uncertainties in fatigue performance of new, higher grade steels for chains, combined out-of-plane bending and torsion fatigue, accelerated failures by; fatigue crack growth propagation, possible overload and issues arising from manufacturing defects. Inappropriate repair actions (i.e. in-situ re-welding of studs) has also been cited as a potential failure cause [18].

WIRE ROPES

Potential degradation mechanisms for wire ropes and associated hardware include:

- Stress / strain concentrations at discontinuities
- Tension, out-of-plane bending and torsion fatigue
- Wear
- Corrosion
- Overload
- Manufacturing defects
- Damage during handling or installation

Wire rope is particularly vulnerable at terminations (e.g. sockets) because the mass and stiffness discontinuities between the wire rope and terminations can lead to tension, torsion and bending behaviour which leads to stress and strain concentrations and other phenomena such as crevice corrosion. In the thrash zone, steel wire ropes are particularly vulnerable to compression after impact with the seabed which can cause kinking or bird-caging[13] (especially unsheathed ropes). Flexing of the wire strands can result in a loss of the strand binding material (known as blocking compound) and if

[13] 'Bird caging' is when the outer strands of the wire rope separate from the core strand. If the strain level of the strands exceeds the elastic limit of the material then permanent deformation can occur.

suspended sediments are able to penetrate in the rope structure, then abrasion and corrosion may be accelerated.

The service life of wire rope vary significantly by the geographic location of the moored system. Chaplin et al. in [31] reported that the service life of wire ropes can be influenced by; i) the weight of zinc coating on the strands, ii) the effectiveness of blocking compounds and iii) the influence of seawater temperature on the rate of zinc dissolution (Figure 12). This later factor was addressed by a semi-empirical model for wire rope seawater corrosion developed by Fontaine et al. in [32].

Failure mode analysis often reveals the indirect cause of component failures. For example, an investigation into the cause of the failure of two wire ropes on a floating storage unit in 2011 implicated contact between the lower wire socket and the seabed. This impact is likely to have caused a transverse oscillation of the wire rope resulting in large bending moments in leeward mooring lines which led to high socket stresses and failure [33]. Gordon et al. provides further insight into wire rope failures in [22]. Common to all line types (rope, chain and wire) careful attention should be paid to lines which go slack in storm conditions as this could result in large device motions and possible overloading. This can be mitigated through efficient mooring system design and assessed via condition monitoring and in combination with validation mooring simulation models.

Figure 12: (left) Corrosion and break-up of independent wire rope core (IWRC) of 76 mm ungalvanised MODU mooring rope after five years' service; (right) IWRC of 90 mm galvanised MODU mooring rope after 7 years [31].

3.4 Mooring Subsystems and Components

3.4.1 Shock Absorbers

A number of alternative mooring components are being developed to provide additional axial compliance beyond what is provided by the geometry of the mooring system, to reduce the magnitude of peak loads (and potentially reduce fatigue load levels). It has not been possible to substantiate the TRL, performance, scalability or cost of available shock absorbers as part of this study. While some shock absorbers have been commercialised for small-scale marine applications such as pontoons, their readiness for large-scale WEC applications is largely unproven. A number of shock absorber technology developers are actively investigating the potential to scale their technology. The benefits of shock-absorbers are similar to what can be achieved via nylon rope technology, with the benefit of potentially using smaller mooring footprints to achieve the same compliance (albeit at the compromise of increasing vertical load component at the anchor). Case study Section 6 quantifies the potential reduction in peak loads with mooring compliance based on known costs and performance of nylon ropes and this provides a useful benchmark to assess the performance of shock-absorbers.

Table 6: Example shock absorber mooring components. Note: these systems are at different stages of commercial development and the details in this table are subject to change.

Technology	Image	Apparent materials	Stiffness and damping variation	Apparent or Target MBL
SUPERFLEX®		Stainless steel / elastomer	Passive	up to 13T
Tfi mooring springs and tethers		Elastomer / thermoplastic spring / steel	Passive	up to 300T
Exeter tether		Elastomer / synthetic rope (polyester)	Passive	up to 150T
Seaflex® mooring system and spring		Stainless steel / elastomer / others	Passive	~10T (mooring system)
Intelligent Active Mooring System (IAMS)		Elastomer / synthetic rope (polyester) / others	Active	up to 400T

Several of the shock-absorber technologies have a number of features, the benefits of which may seem relatively complex compared to a long, compliant synthetic rope. However, if their performance and cost can be substantiated and the technology fully qualified and benchmarked against more mature alternatives then they do offer a number of advantages and could also be used in combination with synthetic- or chain-based mooring systems. An integrated mooring leg which allows active control of stiffness and damping (and even power take off), similar to a hose pump is an interesting approach to provide dual functionality (e.g. IAMS in Table 6). Designing for multiple functionalities is a recognised TRIZ technique for innovative problem solving, see Section 5.

3.4.2 Polymer Lined Fairleads and Tensioning Systems

Typically, the mooring line attachment to the device (fairlead) is a highly loaded and dynamic region which tends to dominate fatigue loading on the components there and heavy chains are often utilised. As part of the Marine Energy Supporting Array Technologies (MESAT[14]) JIP, TTI is developing a polymer lined fairlead which means that the synthetic fibre ropes can be on-boarded directly to the device without any chain sections. This has cost, weight, durability and installation benefits. These developments have been built on TTI's experiences of designing and developing polymer lined fairleads and rope protection applications for the O&G and shipping industries. This project was funded by InnovateUK.

3.4.3 Winching Systems for Synthetic Ropes

A number of WEC developers are actively designing systems with permanent winches (e.g. Marine Power Systems). Traditionally winches may be used for rope handling, installation and pre-tensioning. On multilayer winch drums, fibre ropes often tend to 'bury' into preceding layers as the rope cross section can compress more readily than wire ropes. If this is deemed to be a problem, ropes with higher transverse stiffness can be specified or ideally dual drum winches used where one drum is under load and used for the actual winching and the 'spare' line is then transferred to a 'storage' drum. Dual winch systems can also be used to transfer synthetic ropes from transportation reels onto the winch drum of the installation vessel (e.g. Figure 13).

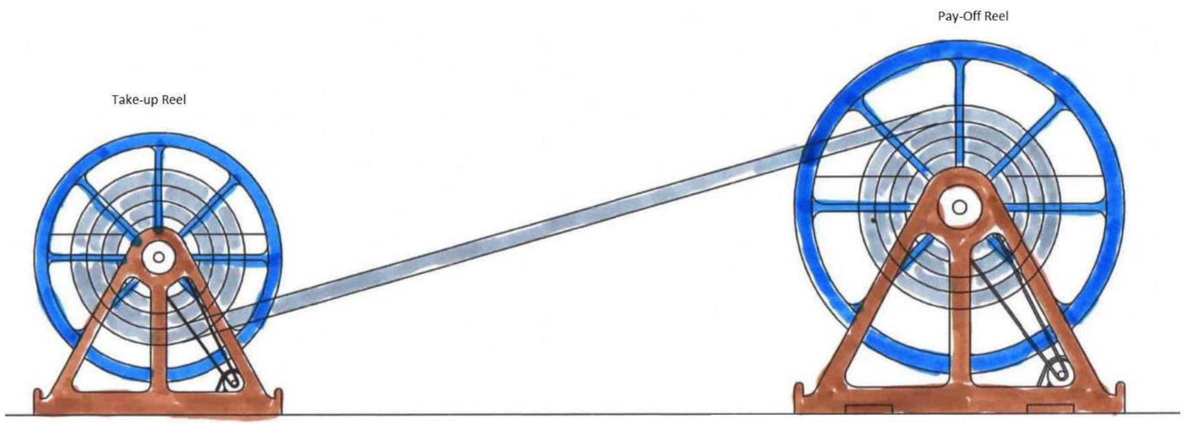


Figure 13: Schematic of two deck winches employed for rope handling.

[14] The £10.5m Marine Energy: Supporting Array Technologies (MESAT) competition launched in February 2012 by the Technology Strategy Board (TSB), Scottish Enterprise (SE) and the National Environmental Research Council (NERC) on common technology challenges associated with marine energy device array deployment and operation.

3.4.4 ROPE PROTECTION, COATINGS AND BUOYANCY

Damage incurred during handling operations is one of the key degradation mechanisms for fibre ropes and as a result suitable working procedures are required during installation and inspection. In addition certain physical measures can be taken. For ropes in 'contact' regions (e.g. on-boarding at fairlead) extremely abrasion resistant wear sleeves can be utilised. These are typically HMPE (Dyneema) braided jackets slid over the rope and spliced in place. With good design of this feature abrasion resistance is maximised and the load-bearing core of the rope is protected. Jackets also provide a visual indication of abrasion and can be replaced.

In addition to jackets, it is common to apply a polyurethane coating to ropes and riser protection nets (RPNs) to protect them from general abrasion during handling. This coating also serves to smooth the surface of the ropes and thusly inhibit marine growth. Some RPNs have been in service for up to 20 years and have not suffered excessive marine growth.

Seabed contact with fibre ropes is to be avoided to prevent abrasion damage. For ropes operating in the benthic boundary layer (close to the seabed) where sediment concentrations are highest a filter layer should be applied between external coatings and the load-bearing core of the rope. This prevents small sediment particles entering the rope structure and exacerbating wear of the rope sublayers.

Buoyancy can be added to ropes using cast on polyurethane collars which floats can then be clamped on to (e.g. Figure 14). These are tested upon manufacture up to 20 tonnes lateral force and they have proven to be resistant to slippage. Alternatively, a single mid-water buoy can be incorporated with the line to add buoyancy if required.

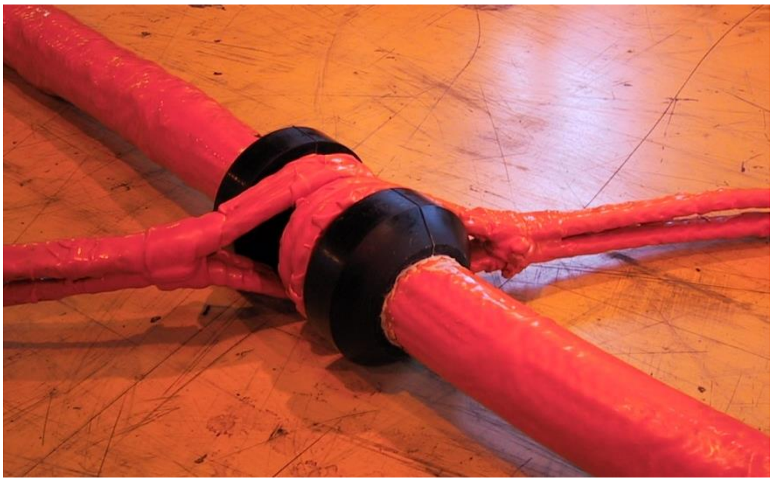


Figure 14: TTI design cast on polyurethane collar on RPN (source: TTI)

3.4.5 NON-METALLIC LINE CONNECTOR OPTIONS

As already established, corrosion of metallic mooring components is a major degradation factor for them and results in numerous mooring system failures. As such, TTI are proponents for the development of corrosion resistant mooring connectors. This may be in the form of engineering polymers or in certain circumstances super duplex stainless steel (SDSS). SDSS is particularly expensive and its use is generally restricted to highly loaded serviceable items such as connecting pins.

Fibre ropes with spliced end terminations usually require thimbles or spools to be inserted into each eye to provide support and an interface between the rope and the pin of connecting hardware.

Conventional mild steel is prone to corrosion, failure and lead to rope abrasion in the corroded condition. TTI has designed and utilised polymer thimbles for this in numerous RPN projects and other applications. These are extremely benign to the rope forming the soft eye and do not suffer from corrosion. Polymer spools on super duplex stainless steel pins also provide a bearing for rotation of the termination minimising effects of bending moments. They also ensure easy removal for maintenance whereas conventional carbon steel shackles corrode and often have to be cut to be removed.

3.4.6 Synthetics Used on Sheaves as Part of the Mooring or PTO System

TTI has observed an emerging trend of WEC devices utilising mooring components as active parts of the PTO system (see VOC survey in Section 4). In other words, the PTO system is ground reacting and the mooring lines transfer the forces to the PTO system, for example, the Fred. Olsen BOLT Lifesaver device prototype tested in Falmouth Bay had three winch-type PTO systems (Figure 15). In principle, this is an attractive concept as it is extracting multiple functions from the mooring system which may bring cost benefits to the overall WEC architecture. However, it also brings with it particular challenges. For example, if the PTO is mechanical-rotary or a hydraulic system it is likely the mooring lines must pass over sheaves. In this case due to the constant motion of the sheaves bending fatigue of the fibre ropes becomes a key concern and design to mitigate this is very important. Typically to improve fatigue life in cyclic-bending-over-sheave (CBoS) the sheave diameter to rope diameter ratio must be maximised. In the case of high PTO and mooring loads a durable rope and also very large sheave diameters are required. To improve the technology readiness level of such systems, TTI recommends that there is a need for specific cyclic-bending-over-sheave studies to improve the component design and demonstrate fatigue performance of subsystems.

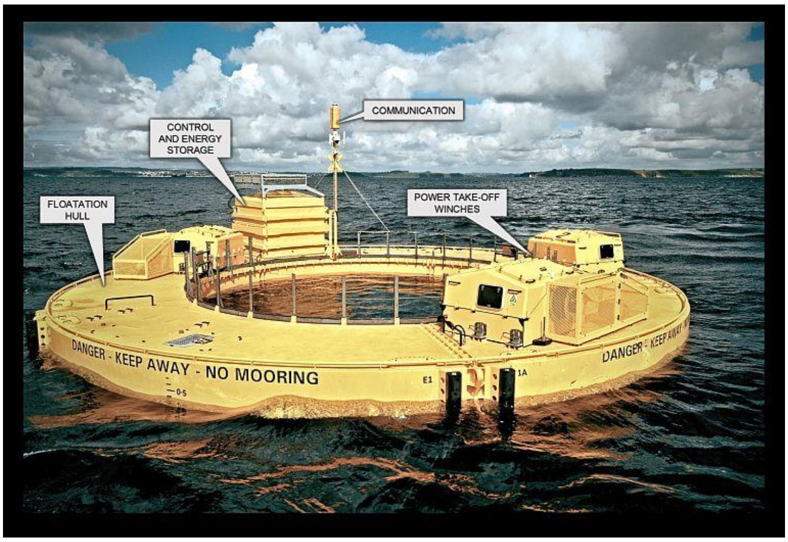


Figure 15: Fred. Olsen BOLT Lifesaver device moored in Falmouth Bay (image source: Fred. Olsen Renewables).

3.5 Connectors and Quick Release Systems

Several connector and quick release systems exist which have either been developed for the offshore sector or more specifically by the MRE sector.

3.5.1 Device to Mooring Connection Systems

A few device developers (e.g. the Floating Power Plant P80 platform) have utilised well-established turret systems akin to those used on FPSO units. The Scotrenewables tidal turbine device also features a turret system which allows the device to be disconnected from the mooring system if the device needs to be recovered from the site.

The Tether Latch Assembly (TLA) system utilised by the Pelamis WEC for connection to the mooring system and umbilical was designed in-house and allowed a significant reduction in the time required for device deployment[15]. Tension was applied to the system by winching of the TLA (similar to a single point mooring; SPM) up to a steel yoke at the front of the device. By having the winch's hydraulic power generation on the winch rather than being supplied by the deployment vessel the significant wave height operational limit was increased from 1.5 to 2.5 m and this subsequently led to a quoted increase in device availability from 70% to over 90% (with average wait time to deploy reduced from 30 days to 5 days). The installation procedure was set out in a way that allowed different stages to be completed at different times, leading to possible reductions in the cost of hiring vessels etc.

3.5.2 Device to Foundation Connection Systems

Several tidal turbine designs utilise self-aligning connection systems to allow the nacelle to be quickly connected and disconnected to the supporting structure and foundation. For example, the AR1500 turbine developed by Atlantis Resources features a gravity stabilisation mechanism (sometimes referred to as a 'hot stab' coupling). For device connection this allows the device to be lowered onto the support structure with a dynamic position (DP) vessel and mated without the need for a locking mechanism. The turbine's electrical and control systems are connected using standard wet-mate connectors used in the oil and gas industry.

3.5.3 Line Component Connectors

The Minesto tidal device utilises a subsea hydraulic mooring coupling system to connect the umbilical to the kite via the system's tether. The connection is made hydraulically using a deployed ROV. Due to the aforementioned issues with metallic connectors, a hybrid multi-material connector for ropes with 60-100T breaking loads was developed in the STORM JIP which comprised TTI, Brunel University London, Nylacast and the European Marine Energy Centre (EMEC). The design (developed by TTI) utilised a low friction, high wear resistant nylon liner (Nylacast CF072) combined with a lightweight, corrosion resistant core made from a novel Aluminium/Basalt composite (Figure 16).

[15] A pick up line and buoy were attached to the TLA to facilitate this process.

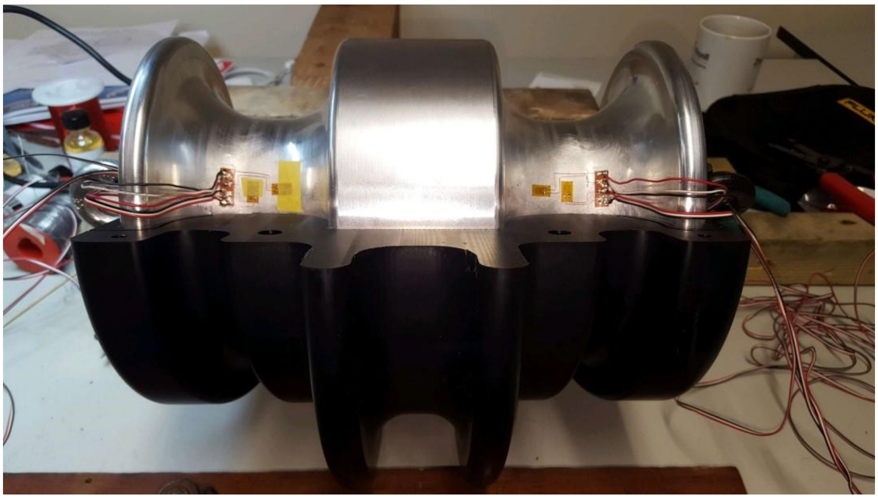


Figure 16: Section of the connector showing aluminium/basalt composite core fitted with strain gauges ready for testing (source: TTI).

3.6 Foundations Categorisation

3.6.1 General

The selection of anchors for offshore installations is primarily based on the occurring geotechnics and loads which are to be applied. Referring to Figure 17 the main types of anchors utilised are:

- Gravity base
- Drag embedment
- Vertically loaded drag embedment
- Driven Piles
- Drilled and grouted piles
- Caisson/suction

In addition, more novel anchor types may be considered for WECs such as rock bolts and hybrid combinations such as gravity and drag or pile/pin and gravity.

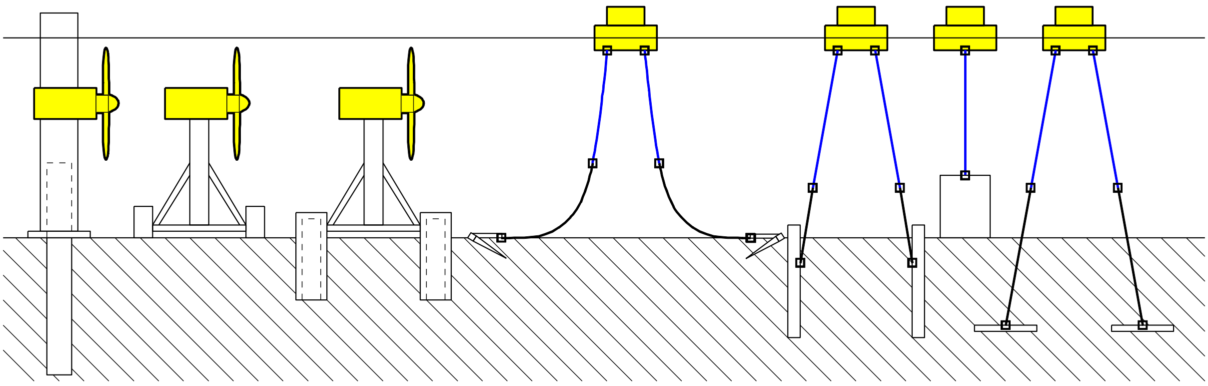


Figure 17: Schematic of possible foundation arrangements for MRE devices: (from left) piled foundation, gravity based structure, suction pile or caisson and several anchor types (drag embedment anchors; DEAs, pin piles, gravity based anchors; GBAs and vertical loaded anchors; VLAs) reproduced from [34].

3.6.2 GRAVITY BASE ANCHORS (GBAS)

Gravity base anchors are likely the most simple anchor type and are functional for almost all seabed conditions. They use mass to mobilise seabed friction to give horizontal resistance. They can accept vertical loads but then the normal reaction is reduced and horizontal capacity is reduced. Depending on the seabed and anchor material coefficients of friction may typically be 0.5. A variant on this type of anchor are shallow foundations, which in addition to bulk mass have a perimeter skirt and shear keys on the base to improve resistance to lateral sliding (and hence horizontal load capacity). Denser anchor materials require less mass-in-air (as anchor displacement is reduced) which has operational benefits (easier to handle, lower capacity vessels etc). However, high-density anchors have much greater material costs. Very large gravity anchors can be designed and installed in a modular fashion to allow the use of smaller construction vessels but the trade-off between day rate and time required to complete the anchor must be examined. A larger vessel which would install the anchor in one operation may be more cost-effective. Figure 18 gives an example of the sensitivity of anchor mass for a range of densities and friction coefficients for a notional taut mooring spread with ~18° line angles and very modest line loads. As shown, low-density anchors require very large masses in air to generate sufficient holding. The benefit of higher friction coefficient is clear.

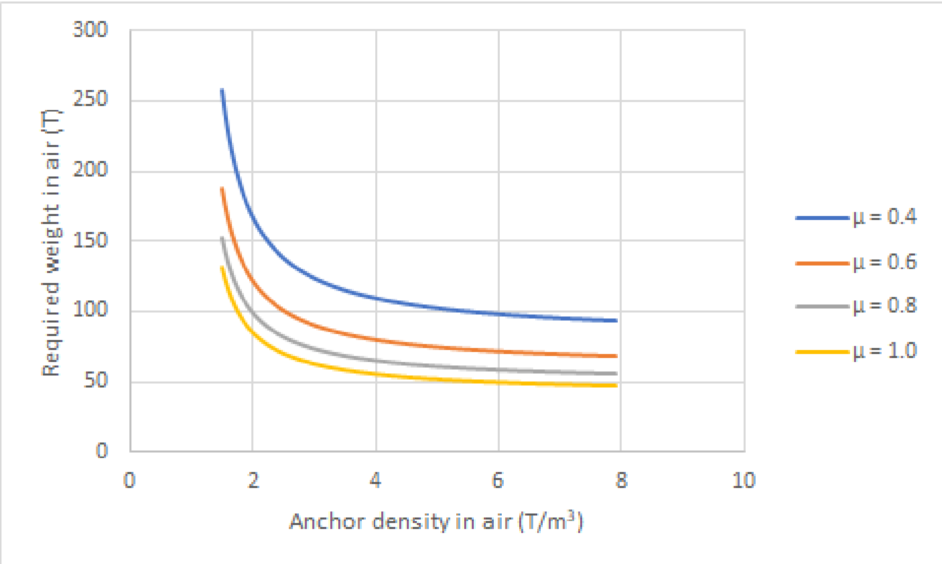


Figure 18: Required GBA mass for different anchor densities and seabed friction coefficients (source: TTI)

TTI in partnership with industrial collaborators including Vryhof engineering has developed and deployed a prototype gravity anchor (as part of the MRCF JIP) which utilises geotextile fabrics to contain locally sourced ballast (e.g. gravel). Numerous sub-bags of ballast are agglomerated using a fabricated fibre rope 'net'. This system conforms to a wide range of seabeds and as such has a high friction coefficient. This system is modular, easy to install, environmentally benign and is projected to have an exceedingly good cost basis compared to other gravity anchors. Figure 19 shows the bag anchor at the design stage and Figure 20 an earlier prototype undergoing lift trials.

The prototype anchor bags are designed to be deployed using a multicat vessel. Despite the relatively low density of the aggregate fill material this approach results in a gravity anchor which is more cost effective than simple fabricated clumps of scrap mooring chain in terms of cost per anchor holding capacity. As part of the MRCF project some initial studies were conducted to assess the scalability of the technology.

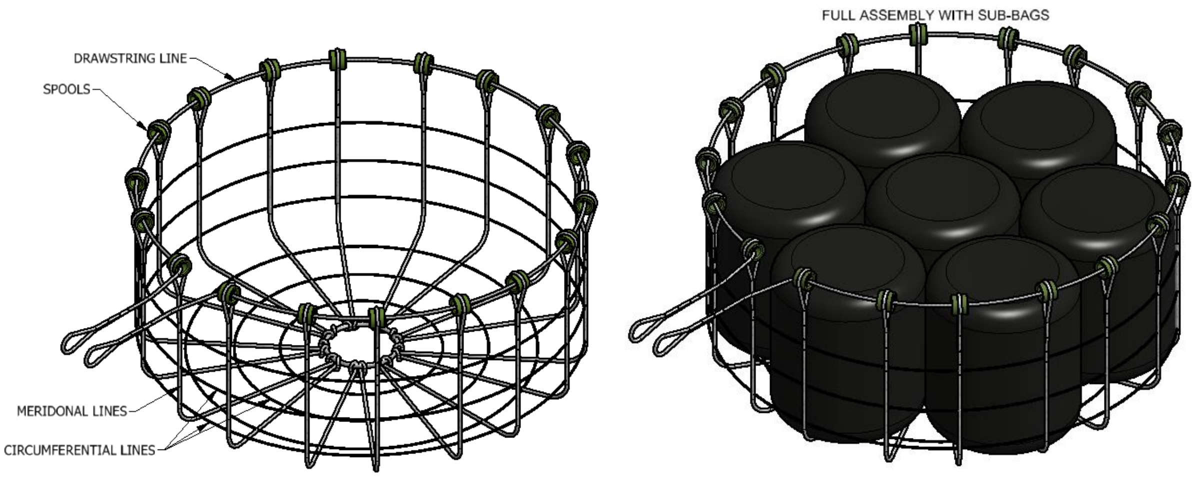


Figure 19: Anchor bag net and filled with sub-bags of ballast (source: TTI).

Figure 20: Early anchor bag prototype undergoing lift trials (source: TTI).

Gravity anchor sizing requires careful analysis to ensure anchor fastness and stability. This is especially the case in shallow water where significant wave loading of the anchor itself can occur due high-water particle velocities near the seabed.

For softer sea beds gravity anchors can often utilise a 'skirt' to penetrate the seabed and therefore command high friction coefficients or "trapped mass".

Stiff anchors (e.g. concrete blocks or steel fabrications) may require a degree of seabed preparation if it is hard and particularly uneven.

3.6.3 Drag Embedment Anchors (DEAs)

Drag embedment anchors generate holding capacity in the seabed as a result of being pulled by the installation vessel. The anchor descends through the soft layers of sediment and maximum holding power is dependent on the embedded depth and surface area of the plates or 'flukes' which are in contact with the sediment. These anchors are capable of holding mooring forces many multiples higher than the mass of the anchor (say between 10 and 100 times anchor mass) but this depends greatly on the anchor type, soil characteristics and embedment depth. Softer and thus weaker soils require embedment depths of up to 25 m to achieve ultimate holding capacity whereas more cohesive soils may achieve ultimate holding in as little as 6 m sediment.

Due to the energetic nature of WEC farm sites the availability of sufficient sediment depth is questionable, especially for the shallower water depths and this may rule out the use of drag embedment anchors for some sites.

Typically drag embedment anchors are regarded as 'zero-uplift' anchors. However, recent experience shows that certain designs may be able to accept uplift at the anchor of around 18° or less. For shallow water depths with a moderately large footprint, this may allow the use of conventional drag embedment anchors.

3.6.4 Vertical Load Anchors (VLAs)

Vertical load (plate embedment) anchors are essentially a developed variant of conventional drag anchors such that they can accept much greater vertical loads. The anchor is installed in a similar fashion and when installed the mooring line attachment point 'switched' from installation to operation geometry which allows vertical loads to be accepted. The anchor relies on the soil above it to achieve good vertical holding and as such requires embedment depths on the upper end of normal drag anchors. This certainly precludes their use for many shallower water WEC sites. However, if sufficient sediment is available these anchors may allow a very cost effective mooring system and farm cost-effectiveness as e.g. taut fibre rope moorings with the smallest footprint may be possible.

3.6.5 Pile Anchors

Pile anchors are essentially steel (or otherwise) tubes which are embedded into the seabed. They can accept horizontal and vertical loading. In soft soils they may be hammered in but are not particularly suited to dynamic vertical loading (e.g. if you can hammer it in you can pull it out). This case requires a depth of sediment above the bedrock so has the same constraints as with drag embedment anchors. For WEC farms it is possible that hammered piles will not be used, as when sediment is available drag embedment anchoring is likely to be a more attractive solution.

For hard rock seabeds the piles may be inserted and grouted into drilled sockets. These anchors achieve very high vertical load capacity and suit taut mooring systems with high uplift at the seabed. The installation is the biggest drawback with these piles as moderate cost inshore construction jack-up barges may be able to install them in shallow water but above say 20 m water depth offshore jack-ups or drillships are required which is deemed beyond the commercial appetite for WEC farms. Some companies are developing subsea drilling templates which are connected to the vessel via an umbilical, but this is very much a developing sub-sector. Such a system was used to install the monopile for the Voith Hydro tidal turbine at EMEC in 37 m of water. Even then, an expensive DP3 vessel of 18151 gross tonnes was required for the operation.

3.6.6 Caisson/Suction Anchors

These are used extensively in the O&G industry especially for TLP moorings in deep water as they are capable of accepting large vertical loads. They are essentially a large diameter pipe, closed at the top. They are 'sucked' into the seabed sediment by pumping out the contained water. Clearly they require a significant depth of sediment so have the similar site restrictions as drag and hammered pile anchors.

For this reason it is unlikely that these will be used at shallow water WEC sites which have high water particle velocities at the seabed, due to the potential for loss of sediment through scour.

3.6.7 Rock Bolts

Rock bolts can be regarded as micro-piles and they are extensively used on land for slope and tunnel stabilisation. Instead of utilising large drillships or jack-ups the concept is to use many smaller piles which are drilled in by a small subsea drill rig. The bolts may be mechanically affixed, grouted or resin bonded. An array of bolts may be deployed on a template such as a concrete or steel slab which may also provide temporary restraint for the drill assembly.

Various organisations are developing subsea drill rigs which could be utilised. Extensive site geotechnical surveys, including boreholes, will likely be required to assure that the rock type is suitable for this method. One example of this is the micropile, which featured in the solution list generated in the Mooring and Foundation Innovation workshop (Section 5.3.3). For example the Raptor Rock Anchor which has been applied to the PLAT-O tidal turbine platform [35].

3.6.8 Hybrid Anchors

As briefly described above anchoring solutions are specific for each site and mooring system and each solution has drawbacks. In turn, novel solutions should be considered which, for example, provide the horizontal restraint of drag anchors with the vertical restraint of gravity anchors. By combining solutions the most cost-effective system may be found. Examples of hybrid solutions may include:

- Gravity anchor pinned with rock bolts or piles – Piles increase horizontal resistance, so less mass is required. Base provides piling template.
- Gravity anchor with drag embedment anchor – Gives vertical restraint capability to conventional anchors.

Innovative anchoring systems were discussed during the Mooring and Foundation Innovation workshop (see Section 5.3.3).

3.7 Marine Installation

3.7.1 Installation Procedures

When considering the range of anchor technologies available, the installation procedures and equipment required are likely to be technology dependent, which is why specific installation processes were introduced in Section 3.6. However, the general principles of mooring and foundation system installation are listed below:

- Adequate planning of marine operations is crucial for safe, timely and efficient installations. Part of the planning process will involve numerical analysis to try to capture every eventuality that could occur during transiting and installation (i.e. [36]). General guidance on marine operations and warranty is provided in [37]. For UK waters the Maritime & Coastguard Agency has produced guidance on navigational practice, safety and emergency response in [38].
- Following installation it is prudent to update simulation models based on the as-installed moored system. This is however reliant being able to survey the installed system. For example the station-keeping ability of the mooring system (in terms of expected line tensions and device excursions) is dependent on the accuracy of anchor/foundation placement and this

requires position measurement systems capable of determining where the anchors have been installed (see Section 3.8.2).

- The type of anchor or foundation is dependent on device and seabed type (e.g. drag embedment, rock/sand screws, gravity-based anchors). Therefore, for sites featuring high variability of seabed conditions, multiple anchor types (and hence different installation processes and equipment) may be required.
- Considerations need to be made for the transportation, handling and installation of components to avoid damage either to the components themselves or in the case of unexpected component failure, nearby personnel[16]. Guidance is provided in certification standards [39, 7] and by some manufacturers [40] for this purpose.
- Relevant health and safety procedures must be adhered to at all times. Guidance on this is provided in *'Guidelines for Health and Safety in the Marine Energy Industry'* produced by BWEA and EMEC [41] and more recent Health & Safety Executive '*Construction (Design and Management) Regulations 2015. Guidance on Regulations*' [42]. The Health & Safety Executive and Maritime & Coastguard Agency *'Regulatory expectations on moorings for floating wind and marine devices'* also signposts relevant Health and Safety legislation [25].

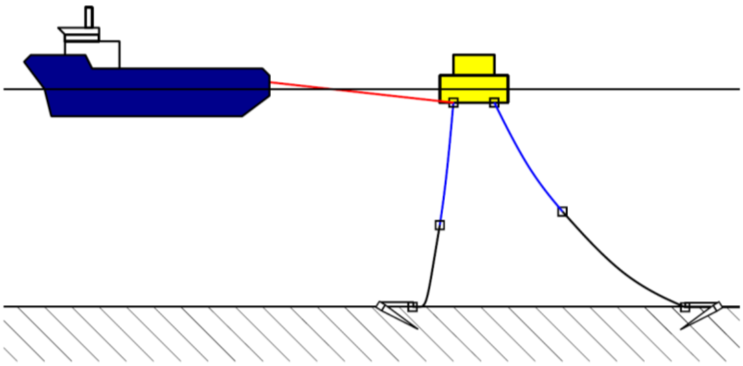


Figure 21: Schematic of fibre rope (blue line) pre-tensioning procedure carried out with an anchor handling vessel (AHV) and detachable chain (red line). Reproduced from [15].

Based on the recommendations reported in [40] the handling of a DEA typically has the following operational steps:

1) The anchor is lowered and then connected to an angle adjuster with a shear pin
2) When the anchor is close to the seabed, the vessel slowly starts moving forward to ensure that the anchor lands correctly on the seabed
3) When the anchor reaches the seabed, the installation bridle or mooring line is paid out. If the anchor does not land correctly, a rerun should be made immediately
4) When enough line has been paid out, the anchor handling vessel (AHV), using its bollard pull, starts increasing the tension in the mooring line. The anchor starts to embed
5) When the installation load is reached, the angle adjuster triggers the anchor to its normal loading mode. The holding capacity suddenly increases, which stops the AHV to move forward
6) The AHV increases the tension until the proof load: the anchor is installed. Pre-tensioning of the lines can then take place (e.g. Figure 21).

[16] For example the use of Snap Back Zones painted on the deck of the installation vessel (or indeed WEC) in the vicinity of mooring equipment, rollers and fairleads which mark a potentially unsafe area when the mooring line is under tension.

3.8 Condition Monitoring

3.8.1 Motivation

Of the number of WEC sea-trials conducted to-date only a few notable projects have reached the higher technology readiness levels (i.e. commercial demonstration at TRLs 7-8). To ensure continued investment, it is necessary for the sector to deliver an LCOE which is on a par with other forms of power generation, requiring technologies to be at a stage where an operational availability of 75% is feasible [43]. As yet, a lack of design convergence and long-term deployments as well as concerns over commercial confidentiality has hampered the sharing of performance and reliability data in the sector. This is symptomatic of the wider offshore industry, with few examples of offshore tension measurements in the public domain (e.g. [44, 24]).

In the context of WEC mooring and foundation systems, condition monitoring provides:

- an indication of loss of functionality of a component or subsystem
- a long-term record for fatigue analysis and modelling
- an early warning of impending failure, which can influence unplanned maintenance actions

Condition monitoring has a particularly important role for new, unusual device designs which may have previously unknown nuances that might not be captured by numerical models, small-scale testing or even short-duration sea-trials.

3.8.2 Condition Monitoring Technologies

A review of current technologies used for offshore equipment has recently been produced by the Health & Safety Executive [45]. The most common form of mooring system monitoring is direct line tension measurement (using load links or shackles) or indirect measurement (using line inclination angle sensors), with examples of such systems provided in Figure 22. Tension measurements have even been used to infer VIV of tendons used on large platforms [46], which could be relevant to taut moored systems situated in high flow environments.

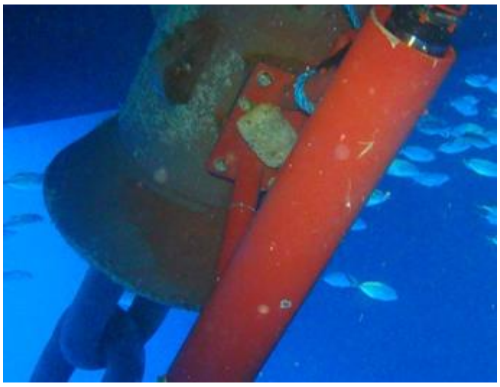


Figure 22: (left) Direct line tension measurement using a shackle load pin (source: UoE). (right) MOORASSURE™ line inclination sensor (source: Pulse Structural Monitoring).

Alternative approaches to direct load measurement have been considered. Research has been conducted to determine if it is possible to monitor mooring system integrity and even line tensions by coupling a device positioning system (i.e. digital global positioning system; DGPS and inertial motion unit; IMU measurements) with accurate numerical models [47]. Alternative condition monitoring techniques that have been proposed include embedded systems comprising optical fibres able to measure strain and variations in synthetic rope stiffness [48] as well as acoustic systems to monitor the onset of rope failure [49]. A recent review of condition monitoring techniques for ropes is provided by Oland et al. in [50].

The accuracy of anchor positioning during installation has a key influence on the response of the moored system. It is often assumed to be within ±5 m for suction and pile anchors [4], and for embedment anchors this is usually determined from vessel position with some allowance made for tripping and embedment. Following installation of the mooring system a side-scan or towed sonar surveys can be used to map the position of anchors and ground chain (if used). A more precise and generally more expensive method utilises an acoustic beacon which is attached to the anchor shackle by a diver. Signals are transmitted towards the installation vessel and once the distance and heading are calculated the results are combined with the vessel DGPS position. A ROV could be used to place the beacons instead of using divers and would incur less risk.

3.8.3 In-Situ Inspection

As highlighted in Section 3.3.4 mooring components are susceptible to several damage mechanisms and this must be considered during system design, component specification and maintenance planning. As part of a maintenance plan, component inspection should be carried out (e.g. [4, 51, 52]). Specific guidance on inspection and retirement procedures is provided by the classification societies for synthetic ropes [53, 54] and also chains, steel wire ropes and associated hardware [55, 6]. Inspection intervals will generally depend on the material used and the loading conditions experienced by the mooring system. Initial inspection typically starts with visual inspections (using ROVs or divers for subsea components). If damage is suspected then the line has to be recovered onto the deck of the work vessel for closer inspection. In the case of jacketed synthetic ropes this may necessitate inspection of the internal rope elements (if the protective jacket can be reinstated prior to re-deployment). DNV-RP-E304 [54] outlines several procedures including estimating the remaining fatigue life and strength of ropes based on the condition of load bearing components, and removal of the rope followed by residual strength tests using tension-tension testing equipment (see Section 3.9.3).

Detailed inspection and maintenance guidance for MRE devices have yet to be developed, and current certification guidelines (e.g. [56, 57]) either refer back to existing offshore standards or suggest intervals based on fatigue life calculations (e.g. [58, 59]). Due to the prohibitive costs of chartering work vessels and the dependency of marine operations on favourable weather windows it is unlikely that the mooring lines of WEC arrays will be periodically removed for inspection. Instead, it is more likely that lifetime calculations will be based on: i) laboratory test data (new and used components), ii) load monitoring (if sufficiently robust and reliable systems are developed) and iii) maintenance schedules that include visual ROV inspections. To reduce operational expenditure (OPEX) costs, line removal can therefore be limited to the areas of the array which are subjected to the brunt of environmental loading, at periodic intervals (e.g. potentially every few years).

3.8.4 Challenges

For all of the benefits of installing condition monitoring systems, details of the failure incidents are typically sparse or incomplete and often failures go unreported (e.g. due to ignored, faulty or non-existent alarms [17]). Therefore it can be reasonably assumed that many more failures occurred globally than those reported in the (already limited) failure statistics that are available. The following example reproduced from [60] illustrates this point:

"…..an alarm on a line tension measuring cell on the Norne FPSO operated by Statoil indicated a mooring line failure. However, the initial diagnosis was an error in the alarm system. The load cells were regarded as unreliable. The significant wave height was 8-9m. The failure was confirmed four days later"

In early 2005 the Wave Dragon prototype was subjected to a large storm (referred to as a '100-year event' in [61]) which led to failure of an inline force transducer and subsequent beaching of the device 400m from its original position. Although little damage occurred this event demonstrates that use of monitoring equipment in critical load paths warrants care and the provision of adequate redundancy measures.

The main challenges for load shackles and links are:

- Prevention of water ingress
- Power supply (hardwired or battery)
- Cable integrity (in the case of hardwired systems)
- Over-strain and/or long-term drift
- Data corruption and storage requirements (clearly linked with power consumption).
- Restrictions on placement and biofouling (for systems which include acoustic data transfer or inclination measurements)

Therefore, while condition monitoring systems have a key role to play to enable short and long-term data capture, there is clear requirement for monitoring systems to have an inherently high level of reliability in order to be a useful addition and also to avoid false-positive events. Autonomous, wireless measurement systems are particularly attractive for long-term deployments. However, at present commercial load monitoring systems tend to be designed for shorter intervals of data capture. For example, the Applied Acoustics Wireless Acoustic load shackle system has a maximum rate deployment life of 72,000 samples or 2 months. Because of the current state-of-the-art there is clearly a need to develop robust systems comprising low power electronics combined with adequate data storage and battery life (or a means of self-generation [45]).

The challenges associated with combined hardware-software systems (e.g. [47]) include i) the availability and fidelity of environmental condition measurements (e.g. wave propagation between the measurement system and WEC and influence of the WEC itself), ii) synchronisation of measurement systems, particularly remotely location systems and also iii) the adequate representation of the moored system. Further information on approaches to system analysis can be found in Section 3.10.

3.9 Role of Component Testing

3.9.1 Motivation

For the MRE sector to achieve the target level of availability mentioned in Section 3.8, the reliability of all components and subsystems must be demonstrated [62] and efficient maintenance intervals developed [63]. In order to determine system reliability, long-term sea-trials are required to highlight weaknesses and validate lifecycle models. This could be for new innovations as well as existing components used in a new application or under different operating conditions. Long-term deployments are by their very nature inherently expensive and carry high risk. Championed in the aerospace, automotive and offshore industries, standardised testing allows components and sub-system to be scrutinised in a controlled environment at relatively low cost and risk at a variety of scales (e.g. [64, 65]). The relevance of applying these test procedures to MRE mooring systems, particularly those which are highly dynamic is debatable [15]. Instead it may be appropriate to adapt or develop specific test standards for the sector.

3.9.2 Steel Component Test Procedures

The test methods required to determine the mechanical properties of steel components is specified by several certification guidance documents (e.g. [8, 6, 5]). For steel chains and accessories such as shackles, DNV-OS-E302 [5] and the ABS guideline [8] outline test procedures for both material and chain samples encompassing available material grades (e.g. R3, R3S, R4, R4S and R5). ISO 20438:2017 [66] also covers offshore mooring chains and refers to other International Organisation for Standardisation (ISO) and American Society for Testing and Materials (ASTM) standards. Guidance for the preparation and handling of material samples can be found in [67]. Specific testing procedures are provided in [5] depending on whether the material form is rolled steel bar, forged or cast steel. Table 7 provides an overview of minimum mechanical property values for chain grades R3, R3S, R4, R4S and R5 encompassing both tensile and impact (Charpy V-notch) testing. A key principle of material testing is using an adequate number of samples (which are representative of the finished product) to avoid differences in strength which could result from cutting or different levels of heat treatment. Further testing on additional samples is allowable if the first sample properties do not meet the specified criteria.

Table 7: Minimum mechanical properties for chain cable materials (reproduced from [5])

Steel grade	*Yield stress* R_e *N/mm²*	*Tensile strength* R_m *N/mm²*	*Elongation* A_5 *%*	*Reduction of area* *Z* *%*	*Charpy V-notch*		
					Temperature [1)] *°C*	*Average energy* *J*	*Single energy* *J*
R3	410	690	17	50 [2)]	0 -20	60 40	45 30
R3S	490	770	15	50 [2)]	0 -20	65 45	49 34
R4	580	860	12	50 [3)]	-20	50	38
R4S	700	960	12	50 [3)]	-20	56	42
R5	760	1000	12	50 [3)]	-20	58	44

[1)] For grade R3 and R3S, testing may be carried out at either 0°C or -20°C.
[2)] For cast accessories, the minimum value shall be 40%.
[3)] For cast accessories, the minimum value shall be 35%.

Thresholds for proof and break load tests can be found in DNV-OS-E302 [55] in the form of formulas related to nominal chain diameter (d), for example the proof and break load of a studlink chain in kN are $0.0156d^2$ and $0.0223d^2$. Clearly it would be impractical to test every link, and as a result maximum sampling length are specified based on nominal chain diameter. Specifications for linear weight and five-link length are also provided. Both [8] and [55] include guidance on non-destructive testing (NDT) techniques which can be applied after testing including non-destructive examination (magnetic particles and dye penetrant) as well as ultrasonic examination as listed in Table 8.

Table 8: Non-destructive testing (NDT) techniques recommended by [6, 5] for wire ropes (WR) and chains (C) and associated hardware

Test	Procedure	Relevance	
		WR	C
Magnetic particle testing of forgings	EN 10228-1, ASTM A275, using wet continuous magnetisation technique	X	X
Ultrasonic testing of forgings	EN 10228-3, ASTM A388, ISO 13588 (C)	X	X
Magnetic particle testing of castings	ASTM E709, using wet continuous magnetisation technique	X	X

Ultrasonic testing of castings	ASTM A609, ISO 13588 (C)	X	X
Magnetic particle testing of bars	ASTM E1444		X
Eddy current testing of bars	ISO 15549		X

A separate set of standards exist for determining the properties of steel wire ropes used in mooring systems (e.g. [6, 68, 69]). DNV-OS-E304 distinguishes between tests applicable to wire ropes used for mobile mooring and towing and those used for permanent mooring systems. For long-term mooring systems distinction is also made between test procedures for the wire rope and socket terminations. For wire rope, an elastic modulus test is carried out prior to dynamic cycling (to stabilise the rope and also quantify load/extension and permanent stretch). This is then followed by load-to-failure test to quantify the breaking load. According to [6] the two criteria that a wire rope must satisfy are: i) permanent elongation of the rope is less than 0.4% for a spiral rope and 0.8% for a stranded rope and ii) the test sample reaches the required MBL. As with chain testing, steel wire ropes and terminations are also subjected to visual inspections and NDT (e.g. Table 8).

Furthermore in order to ensure that the socket termination is fit-for-purpose the test sample must be representative of the finished product. The test procedure outlined in [6] involves loading the socketed assembly to the minimum certified breaking load for 30s followed by magnetic particle testing. The socket assembly is deemed to have passed if: i) the pin can be easily removed and replaced and ii) the NDT requirements specified in [6] are satisfied.

Manufacturers commonly specify a working load limit (WLL) for steel components which is based on the tested breaking load of the component after the application of a suitable factor of safety (e.g. Green Pin shackles tend to a factor of safety of 5x or 6x the WLL before failure under normal operating conditions[17]).

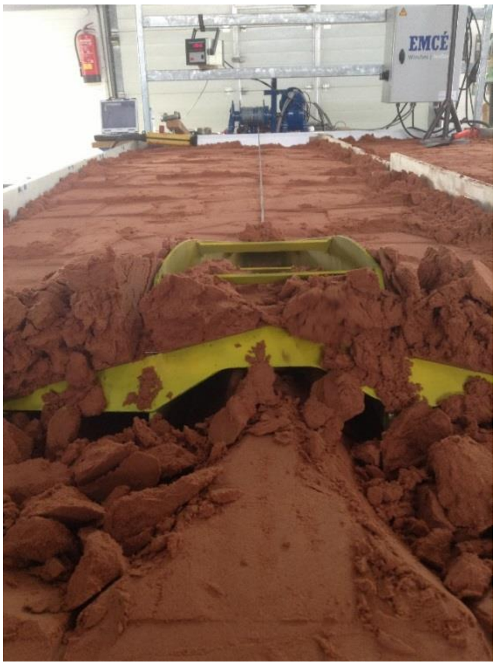


Figure 23: STEVSHARK®REX prototype model testing in foundry sand at the Vryhof Research Facility. This design was later used in the WindFloat project near Aberdeen (source: Vryhof)

[17] Van Beest GreenPin catalogue: http://www.greenpin.com/green-pin

The aforementioned testing procedures are focused on determining the structural strength and material properties of steel mooring line components. Performance testing is also a way of determining the effectiveness of a particular design and to validate numerical models. For drag anchors, this can be carried out at a range of scales both on- and offshore (e.g. Figure 23 and [70]).

3.9.3 Synthetic Rope Testing Procedures

Testing procedures for synthetic ropes have been developed for the offshore industry over the past three decades and can be found in guidance documents produced by the Oil Companies International Marine Forum (OCIMF), ISO, American Petroleum Institute (API), Det Norske Veritas Germanischer Lloyd (DNVGL), American Bureau of Shipping (ABS) and Bureau Veritas (BV) (e.g. [7, 71, 72, 39, 73, 74]). In the context of mooring systems for offshore equipment there are three main test types which are quantified through physical testing: i) tensile strength, ii) cyclic loading endurance (tensile, compression and bending) and iii) other rope properties (i.e. stiffness, core tenacity, linear mass and torque properties etc). An overview of these tests for mobile and long-term moorings is provided in Table 9. For further discussion on the suitability of these test methods for WEC applications the reader is directed to Section 3.3.3.

Table 9: Test parameters outlined in DNV-OS-E303 [7]. '3-T' refers to tension, time and temperature.

Test	Relevance	
	Mobile	Long-term
3-T performance characteristics (new)	X	X
3-T performance characteristics (used)		X
Cyclic endurance test		X
Splice integrity	X	X
Change-in-length performance	X	X
Breaking strength	X	X
Torque and twist	X	X
Soil ingress resistance	X	X

Tensile Strength

Tensile load-to-failure tests serve three purposes. First, they provide a benchmark of overall strength (the minimum break load or MBL) which is then used in the selection of appropriate ropes in mooring design (with suitable factors of safety applied). Second, the load-to-failure test indicates the load-extension behaviour of a rope sample subject to quasi-static loading, which can be utilised in mooring system design (see Section 3.10.2). Although the test procedures differ slightly between the relevant standards (i.e. [73, 39, 74, 7]) the general approach is to first bed-in the rope through repeating cycling and then apply tension at a constant load rate until failure. To avoid damaging measuring equipment it is usual practice to measure the extension of the free sample length using video-extensometer equipment. Thirdly, it proves the whole system i.e. the rope eye and splices and most importantly the variability of the whole production process including splicing.

As highlighted in Section 3.3.4 there are several potential mooring component damage mechanisms which must be considered during all stages of system design and planning. Load-to-failure tests may be carried out on both new samples as well as from ropes used in service, such as those requiring residual strength analysis following routine inspection [75, 54].

CYCLIC LOADING ENDURANCE

In order to determine the durability of ropes and yarns two standardised test procedures have been developed, the thousand cycle load level TCLL test [71] which is used to obtain a first indication of the tension-load cycle or T-N curves, and yarn-on-yarn abrasion tests [76]. The TCLL test was originally developed for nylon hawsers and includes subjecting rope samples to several load levels, starting with 1000x cycles a load range of 2-50% MBL and followed by further 1000x cycle intervals with higher maximum loads (60%, 70% etc.) until failure. The TCLL test has been very effective for purchasers to rank the relative fatigue life of ropes, i.e. the higher the TCLL - the longer the life of the rope. This works very well for nylon SPM hawsers which suffer internal abrasion. Similar cycling tests can be conducted to produce T-N (tension – number of cycles, e.g. Figure 24) to enable mooring system fatigue calculations such as fatigue limit state (see Section 3.10.2) to be carried out. In [27], Ridge et al. reported on tension-tension cyclic fatigue tests on nylon rope samples subjected to load ranges between 40-70% BL with a mean load equal to 40% BL. These samples were cycled until failure and it can be seen that both nylon and polyester have superior fatigue resistance compared to chain and wire ropes. ISO has produced relevant fatigue test standards; ISO19336 for the compression and tensile fatigue testing of polyarylate materials [77] and ISO18692 for the tensile fatigue testing of polyester [72]

It should be noted that these two standards are intended to provide insight into the residual (break) strength after cyclic loading as opposed to fatigue loading until failure. It may be prudent to measure sample temperature during these tests also to ensure that it does not exceed the design temperature [7]. Accelerated testing of irregular load spectra has been suggested as an alternative to using regular loading cycles [78]. The suitability of this approach needs to be further investigated though, in particular the influence of load time-series acceleration on the temperature load bearing yarns and hence material properties.

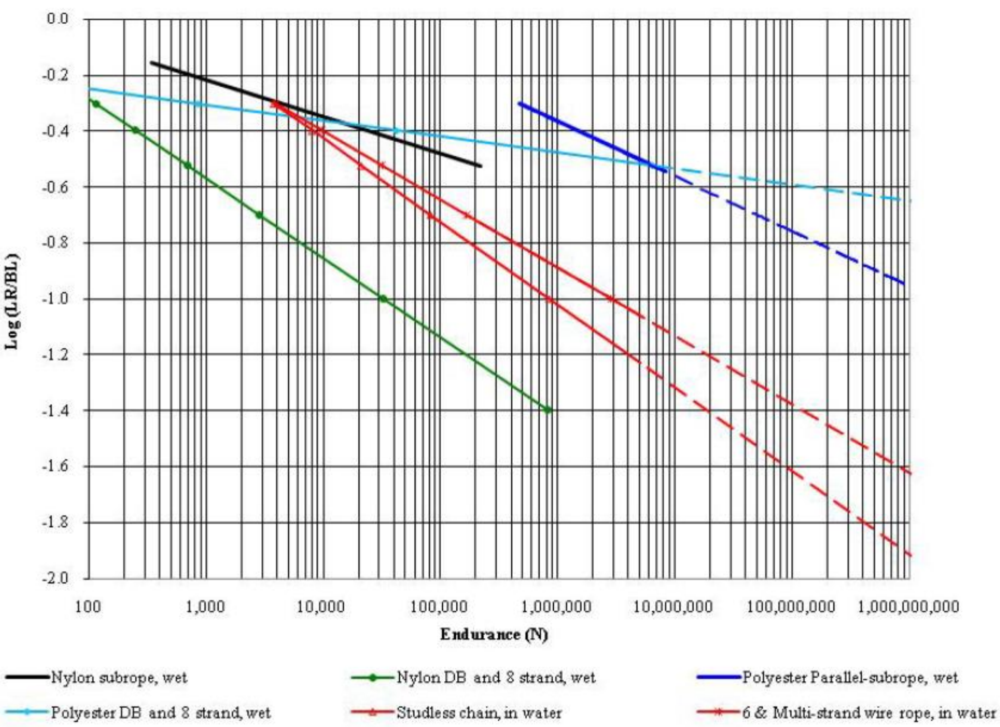


Figure 24: Example fatigue endurance results, produced by TTI, of several synthetic rope constructions, steel chain and wire for various load range to break load (LR/BL) ratios. Reproduced from [27].

Although bend-over-sheave endurance testing is also conducted by several organisations (e.g. [79]), surprisingly there is no standardised procedure for this type of testing. Testing of round and flat ropes running over sheaves is highly relevant for WEC PTO systems which operate like winch drums.

Because fatigue failure is largely caused by friction occurring between adjacent yarns, the yarn-on-yarn cyclic tests are conducted to determine the effectiveness of friction-reducing marine finishes (shown in Figure 25). Whilst it is not possible to directly use yarn-on-yarn abrasion performance to estimate rope fatigue life due to the presence of other mechanisms [15], yarn-on-yarn results can be used to rank rope performance.

The TCLL test might be appropriate for high load range MRE applications. However, further studies are required to determine fatigue performance for loading regimes which feature low tension, moderate and high load range effects.

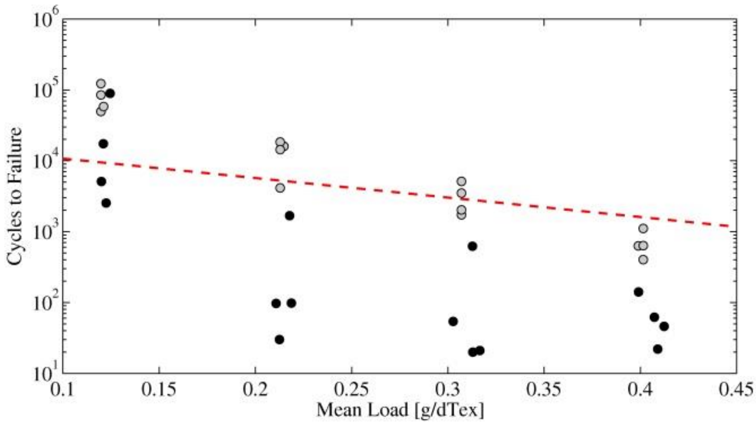


Figure 25: (left) Yarn-on-yarn abrasion test machine at IFREMER, (right) Yarn-on-yarn abrasion tests of new and aged nylon yarns (grey and black markers respectively). Both images reproduced from [13].

General Rope Properties

General properties such as stiffness, core tenacity, linear mass and torque properties are also defined in the aforementioned test standards. Of particular interest to mooring system designers is the load-extension behaviour of ropes subjected to static and dynamic loading as axial stiffness is dependent on loading history, applied mean load, load amplitude and (to a lesser extent) load frequency. In ISO18692 [72] a procedure for determining the quasi-static and dynamic stiffness of samples is provided by utilising a measured extension of the rope at several stages through the test. As discussed in Section 3.3.3 the time-varying behaviour of synthetic ropes warrants consideration due to its potential impact on the response of the moored device. However, most standards do not include the measurement or quantification of this behaviour, with the exception of recommended practice DNV-RP-E305 [80]. Further work is required to determine if the procedures outlined in [80] are applicable to MRE mooring systems.

3.10 System Design and Analysis Considerations

3.10.1 Environmental Aspects

It is not the purpose of this section to describe in detail various locations where WECs may be located but to briefly describe likely characteristics of typical sites as this provides an important frame within which the device mooring system must operate and survive.

WATER DEPTH

Typically, floating WEC devices are located in the near-shore zone with water depths ranging from around 25m as a minimum up to 150m (refer to the VOC survey presented in Section 4). Moving to greater water depths has advantages in terms of energy absorption but this can increase project costs due to shore interconnection and access. Conversely the mooring costs and structural loads can increase when water depth is shallower, while lower associated wave resource can also impact on the cost of energy. Depending on the type and scale of the device, array and wave climate, there will likely be an optimal water depth for deployment based on farm LCOE.

SEABED CONDITIONS

The range of seabed conditions which may be encountered at WEC sites is extensive and can be highly variable over the footprint of the mooring and the array. Nearshore wave energy sites tend to be high energy environments and high water particle velocities at the seabed can result in limited sediment cover which is also likely to be highly mobile and not to be relied upon for drag embedment anchoring. Even in deeper water availability of sediment may be limited in terms of sediment depth, type and distribution. The range of rock types and substrate will also impact on anchor selection and cost.

What is clear, is that seabed conditions are an important boundary condition in the mooring system design and extensive and detailed surveying is required for specific locations before the most appropriate anchoring solution can be selected (i.e. Figure 26). The survey cost must be included in any wave farm project economic assessment and is usually appreciable. The development and adoption of cost-effective site investigation technology and operations could provide significant benefits for the sector.

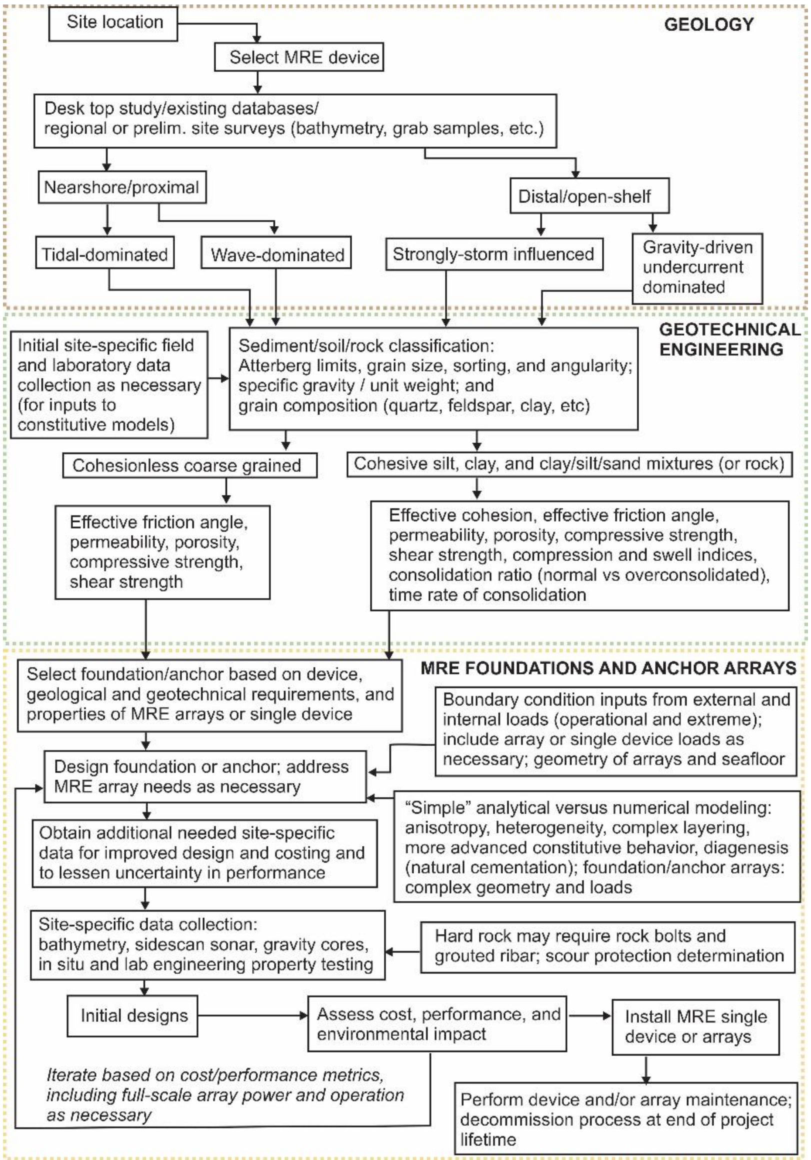


Figure 26: Flowchart for the selection, design, and installation of foundations and anchors. Reproduced from [81].

METOCEAN CONDITIONS

In this section several metocean conditions are discussed with indicative sources of information referenced. Ideally metocean data specific to the site of interest should be used from appropriate sources (e.g. determined by metocean specialists).

WATER LEVEL VARIATION CONSIDERATIONS

Water level variations can be important for some mooring system types, for example it can impact relative device submergence in the case of systems with low compliance (such as TLPs). The water level range can impact on relative device submergence for low compliant moorings The *Environmental Considerations OTO2001/010* report produced by the Health & Safety Executive [82] gives indicative spring tide amplitude and surge height contours around the UK. Atmospheric effects such as surge can significantly influence both the maximum and minimum water levels. In such circumstances use of the astronomical tidal range for design purposes could be erroneous. More up to date extreme water level (EWL) data, than in OTO 01/010 for UK waters (based on gauge measurements) are provided in Environment Agency document *"Coastal Design Sea Levels"* [83]. Taut mooring systems must provide sufficient compliance to allow the WEC to float at constant draught (unless the device is designed to be draught insensitive). The capability of different designs and materials to provide this compliance is discussed further in Section 5.

DESIGN WIND

Typically, many WECs are low freeboard so wind loading is a small percentage of the total environmental loading but should be considered for design all the same. HSE Offshore Technology Report OTO2001/010 [82] provides wind speed contours around the UK.

DESIGN CURRENT

Contours for tidal current velocities[18] around the UK are provided in [82, 82]. It is shown that typical velocities can be up to several knots in speeds.

While total hydrodynamic loads tend to be dominated by waves, certain wave technologies can be particularly sensitive to surface currents. For example, a floating attenuator designed for wave vaning, or with a degree of yaw compliance, may align itself with the current rather than the wave direction. This effect can result in higher mooring loads and may also impact on power capture efficiency.

DESIGN WAVE

The Ultimate Limit State (ULS) of a WEC mooring system is especially arduous as the environments in which the devices are located are generally highly energetic and susceptible to severe winter storms which drive high structural and mooring loads. It is general practice to consider a set of wave conditions comprising significant wave heights and periods along the 100-year return period contour [4]. DNVGL-RP-C205 [84] gives zones for estimation of long-term wave parameters and some scatter diagrams. Health & Safety Executive Offshore Technology Report OTO2001/010 [82] also provides wave height contours around the UK. However, for a WEC farm it would be expected that wave measurement devices be deployed for an appreciable duration to obtain high-quality site-specific information. A incident wave model that has been robustly calibrated for a number of locations can then be used to estimate the wave conditions across the area of the farm array.

The range of significant wave heights experienced by a device are both site and return period dependent. For example, typical design extreme conditions encountered at Atlantic exposed Scottish sites have significant wave heights of between 12m and 15m for water depth range of 50m to 100m with a corresponding maximum wave height of around 28m (this is typical of a 100 year return period). However mooring design cases are different for lower latitude sites exposed to the open ocean. Such sites are likely to have lower design wave extremes with a corresponding lower annual average wave resource (which is also less seasonal).

Mooring loads are also influenced by spectral shape and short-crestedness of the design waves.

COMBINED AND MULTI-DIRECTIONAL METOCEAN CONDITIONS AND THEIR IMPACT ON MOORINGS

The multidirectional nature of environmental conditions at specific sites is highly variable and can have a significant impact on mooring loads and design. Annual and seasonal wind, wave and current roses when overlaid can have a very different profile across different sites. This can be further complicated by three-dimensional nature of the environment which varies over the vertical axis for wind, wave and current in both strength and direction. Waves can be highly multi-directional in terms of the combined swell and local wind generated components and degree of short-crestedness. The interaction of waves with current is at present not fully understood and may not be adequately represented by the

[18] The influence of atmospheric conditions on ocean currents may need to be considered.

superposition of wave-particle and current velocities. Suitable equipment (e.g. acoustic Doppler current profilers, ADCPs) can provide insight into the how current and/or wave hydrodynamics vary in time and space.

Offshore standards such as DNVGL-OS-E301 [4] specify that combined environmental loads should typically comprise wind and wave conditions (100 year return period) and current conditions (10 year return period). The environmental loads should be considered to act collinearly (in-line and in-between directions) unless site data exists which shows that this is not possible (e.g. wave shielding by islands from certain direction). Directional wind, current or wave spectra can also be used if available.

Design environment, survivability and optimal performance all influence mooring design requirements. A point absorber WEC which has symmetry about the vertical axis may be less challenging than, say, a floating terminator or attenuator which could have a fixed heading or variable heading. However, it may prove most cost effective to have an asymmetric mooring layout to match the dominant loading regimes from around the compass.

The requirement for fixed or variable heading will very much depend on the type of WEC and directional variability of the environmental load components acting on the device and mooring. Establishing the ideal fixed heading for a device can be complex and it is important for the WEC designer to understand in detail the directional power capture efficiency (i.e. directional power matrices) of their system in addition to site-specific variability of the resource (i.e. annual and seasonal directional scatter diagrams). For example, for a fixed heading device the optimal performance heading for the device to maximise annual energy yield may not always necessarily be aligned to the directional sector contributing most to the annual average energy resource. Further, the optimal heading for survivability may be a different heading. These competing factors might then point to the requirement for a variable heading device (e.g. weather vaning).

Weather vaning has the advantage that it likely reduces mooring loads and can optimise device performance for differing wave incidences. However, it is likely that increased device spacing will be required to allow vaning which affects array density. Further, the device sensitivity to side currents and the total mooring force must also then be considered.

Weather vaning moorings may be similar to catenary anchor leg mooring (CALM) and single anchor leg mooring (SALM) systems typically used for O&G buoy moorings with the device attached to the buoy by a hawser or fabricated yoke. Similarly, if the device is moored as a CALM buoy then it may have a turret system as part of the device hull which allows the device to rotate. Turret based moorings can be fairly complex and depending on the application and scale could have a significantly detrimental influence on device economics.

One of the challenges for wave technology developers is whether to opt for passive or active weather vaning. In the context of this study passive vaning infers that the device has inherent wave alignment capability, whereas active vaning could be enabled for example by winching. Heading control preferences will also depend on the dominant load (e.g. does a device tend to align with wind, wave or current forces). The dominating load will be dependent on the magnitude and direction of wind, wave and current. One of the challenges for large floating attenuators is that coastal currents tend to run obliquely to predominant wave direction, which can cause a yaw offset in the device which could impact on performance (positively or negatively) and survival loads.

Intuitively a passive vaning system would have a lower CAPEX and OPEX than an active vaning system. However the impact of using passive vaning on power production (and hence total LCOE) may be insignificant and not technically viable. There may be scenarios whereby an active vaning system is deemed to be more cost effective in terms of LCOE and also more feasible than passive vaning. The relative merits of both approaches warrant further research.

3.10.2 Mooring System Analysis

While preliminary design guidelines have been developed for the MRE devices [57, 56], the analysis processes and factors of safety contained therein are ultimately based on existing offshore guidance (e.g. [85, 4, 86, 87, 88, 36]) developed for the oil and gas industry. Use of an overly conservative approach to mooring design is potentially onerous and unnecessary for MRE array developments because the consequence of mooring component failure for mainly unmanned equipment is less severe than for oil and gas equipment [89]. However, should a failure occur sufficient system integrity has to be maintained to ensure the health and safety of personnel on or near the installation [25]. The development of appropriate standards and design guidelines should therefore be made a priority and is in progress for the next version of the IEC TS 62600-10 guidelines [57]. A reduction of the factors of safety used in mooring and foundation design is only likely to occur if the WEC sector can demonstrate to the classification societies that lower factors of safety are appropriate and this would require cross-sector coordination and knowledge sharing.

The procedure for determining the suitability of a particular mooring design is similar for most certification guidance. Firstly, the site and metocean conditions are determined and a set of scenarios are identified (Section 3.10.1). Then the initial complete design is scrutinised via quasi-static and/or dynamic numerical modelling to check that:

a) Components have sufficient strength (i.e. minimum break load) with a suitable factor(s) of safety to withstand applied line tensions
b) Device excursions are within an appropriate envelope – to avoid damage to the power export cable/umbilical or clashing with adjacent devices
c) Line clashing does not occur
d) Line uplift angles at the anchoring point are acceptable – critical for certain DEA designs

In DNVGL-OS-E301 [4] this series of checks is called ultimate limit state (ULS) utilising partial safety factors. It is then followed by accidental limit state (ALS) checks where one line is removed at a time to simulate a line failure. Dynamic simulations tend to be based on a set of scenarios with 3-hour sea-states to adequately capture extreme line tensions and device responses resulting from wave- and low-frequency processes in conjunction with wind and current loading. While the use of 3-hour simulations is the standard method of determining stable statistics, research has demonstrated that this duration may not be sufficient for low-frequency responses of the order of 100s – 200s [90].

The ULS and ALS checks are applied to ensure that the mooring line components are sufficiently robust to withstand extreme, peak loading conditions. Cumulative damage over longer time-scales due to repeated cyclic loads can also occur (see Section 3.3.4) and this is particularly relevant for devices located in energetic environments. For this reason, fatigue limit state (FLS) analysis is carried out, utilising rain-flow analysis to discretise the simulated or measured tension (T) time-series into a number (N) of tension or stress (S) cycles [91]. Typically T-N (synthetic ropes) or S-N (steel components) design curves are based on the mean of data minus 2 standard deviations. The Pålmgren-Miner rule is then used to calculate the overall damage sustained by the component by combining all of the damage contributions at each stress magnitude or tension ratio. This approach is widely used, despite having two key shortcomings [92]: i) damage is accumulated by discrete events (i.e. load history and its effect on material state are not considered) and ii) the rate of damage accumulation is independent of stress or load level. Furthermore, the suitability of this method has not yet been verified for MRE mooring system components and this requires further research, in particular if its use leads to under- or over-conservative designs.

DEVICE REPRESENTATION

Commercial mooring system software developed for the shipping, petroleum and offshore construction industries has many features that can be used to carry out static, quasi-static and time-domain modelling of floating WECs including: ProteusDS, Orcaflex, Optimoor, Deeplines, DIODORE, ARIANE7, Sesam DeepC and AQWA Suite. If wave diffraction is not expected to occur (i.e. when the principal dimension of the device is small compared to the expected incident wavelengths), the device can be represented by Morison elements in most commercial software. For large structures that diffract and interact with neighboring devices, hydrostatic and hydrodynamic responses of the device can be calculated by boundary element software (based on potential theory) such as WAMIT, NEMOH, AQWA, WADAM and Seasam HydroD. The results of which can be imported into commercial mooring system software (time domain modelling) or alternatively used to rapidly approximate device response (in the frequency domain). The use of first- and second-order motion and load coefficients, added mass and radiation damping calculated in this way is widely applied to the design of offshore equipment. However it is not possible to easily incorporate the key subsystems of WECs (e.g. PTO and control systems) into most commercial mooring systems software. To fulfil this requirement 'Wave-to-Wire' models such as WaveDyn by GL-Garrad Hassan, ACHIL-3D by Ecole Centrale de Nantes and more recently the open-source WEC-Sim developed by Sandia National Laboratories have been developed to simulate the dynamic response of WECs.

The application of boundary element methods to estimate device response and loading is reliant on two key assumptions including: i) the fluid is ideal (inviscid, incompressible and irrotational) and ii) the first- and second-order linear wave forces resulting from small amplitude waves lead to small device motions. For scenarios involving linear device responses, this approach is acceptable and usually correlates well with experimental results [93]. For scenarios where the variation of calculated hydrodynamic parameters with device position is important (i.e. large displacements leading to changes in draft) or where complex fluid processes such as wave breaking, slamming and viscous effects occur, more sophisticated techniques are required. Viscous effects can either be accounted for in linear models (i.e. the addition of viscous drag or damping using the Morison equation, or non-linear Froude-Krylov forces on the instantaneous immersed surface) or via computational fluid dynamics (CFD) [94]. The processing requirements of CFD is currently prohibitive for multiple interacting devices distributed over large computational domains and furthermore such fidelity may be unnecessary for all stages of a sea-state. For this reason recent research is considering the combined use of BEM-CFD for linear and non-linear processes [95].

GENERAL LINE COMPONENT REPRESENTATION

The analysis of the mooring lines, chains, subsea cables, hoses and other components performed by commercial software tends to be based on the lumped mass method, where lines are discretised into a number of segments along the specified length of the line joined by mass-bearing nodes. Each segment element is subjected to hydrodynamic loading and can have structural properties such as axial, bending and torsion stiffness and (in the case of steel components) Rayleigh damping. Most software permits the use of multi-component lines and allow segmentation to be varied along the line for computational efficiency. Connecting components tend not to be included as separate elements but instead incorporated with longer line sections (with end constraints applied if relevant). Additional hardware such as buoys, weights and bend restrictors or stiffeners, as well as winches can also be included in most mooring systems software usually as separate elements.

The specification of component properties in commercial software can utilise manufacturer's data or for initial scoping studies some software packages (e.g. Orcaflex) feature a catalogue of generic properties for chain, synthetic and steel wire rope. Additional information is also available for material and hydrodynamic coefficients in certification guidance (e.g. [84, 4]). In terms of structural properties this process is relatively straightforward for steel components, for example the axial stiffness of a steel chain can be specified as a single value, which represents the linear load-strain properties of steel within the elastic range. Any requirement for compliance is provided by the catenary effect which is well understood and not addressed further here.

Synthetic Rope Representation

As highlighted in Section 3.3.3 synthetic ropes display complex viscoelastic, viscoplastic and time-dependent behaviour when loaded and unloaded. At the time of writing commercial mooring systems software is not capable of fully accounting for this behaviour and is generally limited to two basic options for representing axial stiffness:

- Linear stiffness – which could be a secant stiffness of a partial or full load-extension curve[19]
- Non-linear load-extension curve method - non-linear working curves may be based on quasi-static load-to-failure curves, either derived from manufacturer's data or tension-tension tests.

Note that these two variables are usually time-invariant for the entire length of the simulation and are akin to conducting tank tests with a simplified representation of lines (i.e. via the use of springs only). The use of a time-invariant stiffness will not capture viscoelastic and viscoplastic effects during large amplitude (e.g. storm) loading, such as tension increases of leeward lines due to recovery effects. Neglecting the damping effects of synthetic ropes (or misrepresenting line stiffness) is likely to under- or overestimate ranges of line tensions and device excursions. Furthermore the natural period of the mooring system may be incorrect which could skew the predicted performance of the device (i.e. the level of energy captured). These aspects all require further R&D effort.

In order to more accurately simulate the static-dynamic elongation behaviour of synthetic rope 2-and 3- slope models were developed by the American Bureau of Shipping (ABS) [73]. This approach uses linear stiffness values which are applied depending on the type of loading being experienced by the mooring system. Therefore, referring to Figure 27 the two-slope model comprises:

- Quasi-static stiffness – the application of mean environmental loads to determine the mean WEC position
- Dynamic stiffness – used for determining dynamic line tensions resulting from wave-induced WEC motions.

It follows that the quasi-static stiffness value is applied initially up to the mean load followed by the dynamic stiffness value for load cycling, therefore ultimately superimposing dynamic loads on top of the mean load as is likely to be the case in severe conditions. The ABS guidance [73] states that the dynamic part comprises both first- and second-order wave loading which is not explicitly stated in the DNV guidance [4]. Subsequently, with the 3-slope model low and wave frequency loads are treated separately. Dynamic adjustment of curves depending on load conditions has also been proposed.

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[19] In this case the axial stiffness value is based on the gradient of a secant line which has ends corresponding to two points on the load-strain profile [80]. It will therefore not capture the non-linear load-extension behaviour that is typical of synthetic ropes and instead give a crude representation of a particular rope stiffness.

Although it is generally accepted that this approach can be used to represent the basic behavior of synthetic ropes subjected to a wide range of conditions, (at the time of writing) no commercial mooring system software is able to capture the static-dynamic model[20]. Practitioners wishing to use this approach in the frequency or time-domain would need to perform each analysis twice in order to combine the mean WEC motions and tensions (run 1) with the dynamic responses (run 2). Some adjustment is required of line lengths or anchor positions in order to retain the same line pre-tensions.

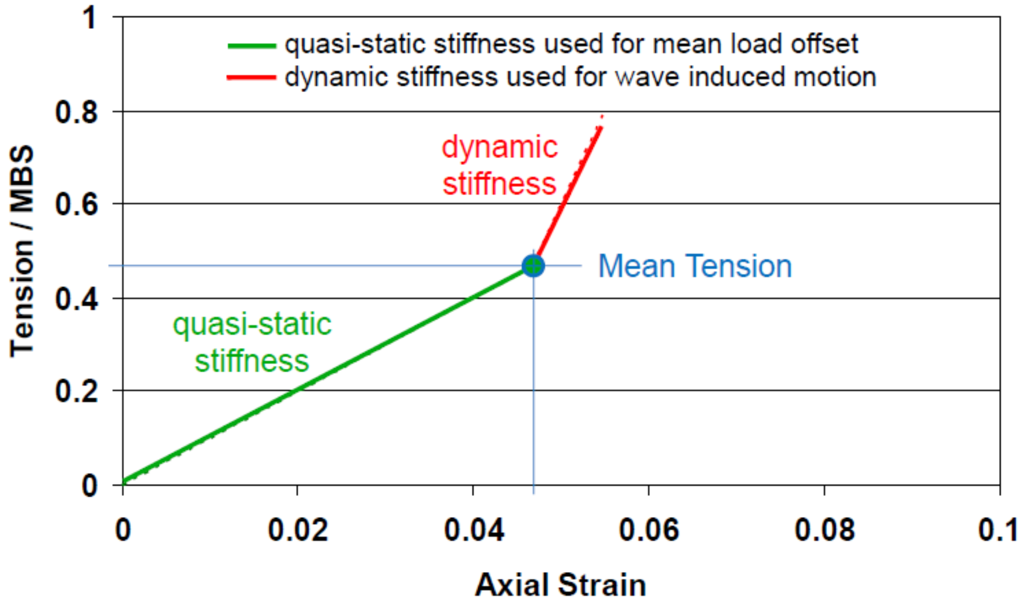

Figure 27: Example modified 2-part nylon stiffness curve (source: TTI)

The methods mentioned above focus purely on the representing axial stiffness. The viscoelastic response of synthetic ropes manifests as a load-unload hysteresis loop due to the phase difference between load and extension changes. This contributes to the overall mooring system damping imparted to the WEC and should be considered during the detailed analysis phase. Furthermore viscoplastic effects resulting from (non-recoverable) creep and constructional rearrangement should be considered to ensure that changes to the mooring system pretension throughout the lifetime of the deployment are accounted for. To address these complexities, the Syrope Joint Industry Project [96] sought to improve previous analysis techniques focusing on mooring systems for mobile drilling vessels (MODUs). Based on a series of physical tests on polyester rope samples the change-in-length characteristics (CILP) were defined for six properties comprising [97]:

- Original, static and dynamic stiffness
- Construction, polymer and working strain

To-date the modelling of the short- and long-term characteristics of synthetic ropes has taken the form of constitutive approaches, material models and finite element analysis (FEA) [15]. Building upon the earlier work conducted in this field, the SynMaRE project [98] which started in 2018[21] aims to develop a practical approach to representing synthetic ropes in commercial software for MRE mooring systems;

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[20] OPTIMOOR features a simplified representation of the static-dynamic model which has been validated against measured tanker and LNGC pier side mooring loads.
[21] Project supported by Wave Energy Scotland via the SuperGen Flex Fund.

providing more detail than time-invariant load-extension curves without the prohibitive computational overhead of FEA.

3.10.3 Foundation System Identification and Analysis

Guidance has been developed by classification societies and other bodies for the design, installation and maintenance of structures, foundations and anchors used in the marine and offshore petroleum industries (e.g. [99, 100, 101, 23]). Similarly, for mooring analysis no WEC-specific guidance documents have been produced by the classification societies for anchors and foundations, although steps have been taken to develop general MRE guidance [102, 103].

The mean load, load range, frequency and direction of loads transferred to the anchor or foundation system from the device either directly (fixed system) or indirectly (moored system) influence the type of seabed connection system that is ultimately selected. This complexity is further increased for WEC array foundation and anchor points which are either in close proximity or are shared. Loading regimes can be broadly split into three categories, each of which potentially has a range of timescales:

- Static loading (e.g. due to the deadweight of the structure or line pretension)
- Cyclic loading (caused by wave, wind and current loading)
- Infrequent loading (impulse loads caused by snatch loading, turbulence, breaking waves, wind gusts, impact and seismic events)

Loading regimes which are highly variable or transient are likely to affect the loading capacity of some seafloor materials. For example, sediment strength can be reduced by cyclic loading and volume changes of drained or partially drained soils [104] and in extreme cases liquefication can occur in low permeability sediments [105]. To date, few studies have considered these effects for MRE foundation-soil interactions [106].

The seafloor conditions of the site also have a significant influence on the process of identifying a suitable anchoring or foundation system and can preclude certain technologies, or even necessitate the use of multiple technologies across sites which have varied geology (see Section 3.10.1). Figure 26 illustrates that this process starts with determining the geology of the site (through sonar survey data) as well as the composition and geotechnical properties of seafloor materials (core sampling and laboratory testing).

WEC foundation analysis is typically carried out on an iterative basis [99] in order to identify a set of suitable design parameters (i.e. foundation or anchor geometry, mass or features). This leads to a holding capacity at the seafloor-foundation interface that is sufficient relative to the predicted design load vectors from the device or mooring line (including suitable factors of safety) which avoid known failure modes. With the exception of purely mass-based systems (i.e. GBAs) most foundation and anchor types are reliant on the additional holding capacity gained by the seafloor-foundation interface as well as (to a lesser extent) line friction on the surface (e.g. ground chain) or partially buried lines. To provide an example failures mode for pile anchors are illustrated in Figure 28. Other failure modes which should be considered in general include bearing capacity failure, overturning, horizontal sliding, slow or non-uniform displacements, undermining and scour, the latter of which has severely affected some wind turbine monopile foundations [107]. Anchors and foundations must also have sufficient structural strength and durability for what is typically a harsh operating environment, with minimal opportunities present for in-situ maintenance or repair. Example analysis metrics are listed in Table 10.

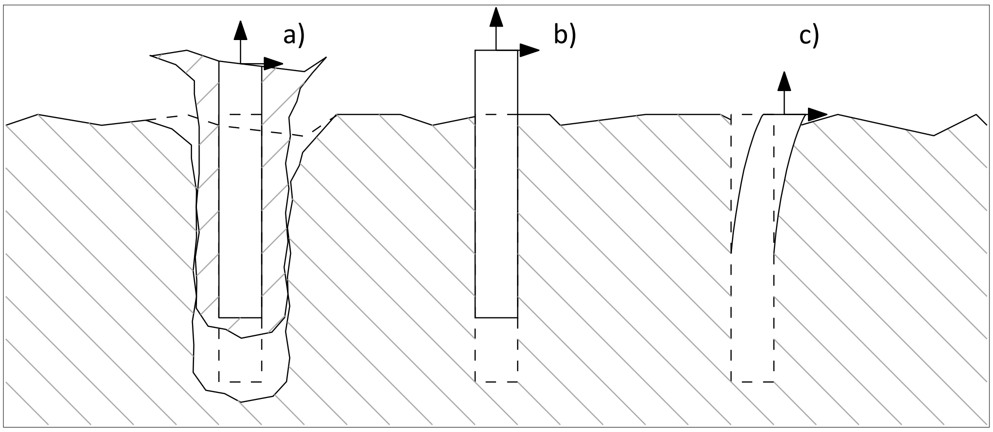


Figure 28: Typical failure modes of offshore piles installed in rock reproduced from [99]: Uplift failure of (a) pile and rock mass and (b) grout-to-rock bond and (c) lateral bending failure of rock and pile

Table 10: Soil-foundation interaction performance metrics considered in [99, 108] and general practice

		Analysis metric
Foundation or anchor type	**Pile**	Lateral load capacity, compressive bearing capacity (including end bearing and shaft resistance), uplift capacity
	Shallow	Compressive bearing capacity, lateral sliding resistance, eccentricity of loading, settlement (i.e. suction below foundation)
	GBA	Compressive bearing capacity, uplift capacity, lateral sliding resistance, eccentricity of loading, settlement (i.e. suction below foundation)
	Suction bucket	Compressive bearing capacity, uplift capacity, failure envelope, embedment due to self-weight and suction
	VLA	Holding capacity, penetration, keying depth
	DEA	Holding capacity, penetration and uplift angle

Commercial-off-the-shelf (COTS) anchors such as DEAs are available in discrete sizes ranked by holding capacity. Manufacturer’s penetration and holding capacity charts enable rapid identification of suitable sizes with empirical relations provided which link ultimate holding capacity, seafloor type and anchor weight. For high-level analysis of short- and long-term loading capacities simple analytical approaches can also be used to estimate the performance metrics of the other anchor and foundation listed in Table 10 [99, 108, 109]. Many of the low-computational overhead design or technology identification approaches are based on experimental tests on prototype anchors and foundations as well as measured geotechnical properties (e.g. the *p-y* curves which are used for lateral pile analysis [23]). Although fast to implement the iterative and piecewise nature of these approaches may lead to designs which are at best suboptimal and at worst may not capture the fundamental load or failure mechanisms.

In reality, the geological composition and distribution of seafloor materials, the influence of bathymetry variations, and the complexity loading regimes experienced by the WEC foundation- or anchor-soil interface lead to a great deal of uncertainty with applying simplified design methods and the necessity to carry out more detailed analysis. Finite element analysis (FEA) can be applied to this task as it is able to model complex foundation- or anchor-soil interactions and processes [110, 111]. Due to the aforementioned complexities which are likely to influence MRE mooring and foundation selection and design, further research is required into the suitability of the material constitutive models employed in FEA for MRE applications [112]. This is particularly important for arrays comprising multiple devices spread over a significant area, necessitating the use of large mesh sizes (refined in the proximity of anchoring or foundation points) coupled with parallel processing techniques.

3.10.4 Global System Analysis

System level analysis featuring multi-physics coupling is beyond the scope of the commercial software packages which are currently available. This would require computational fluid dynamics to capture the influence of wind, wave and current loading on MRE device structure responses, representation of the PTO system and its coupling with fluid flows and load coupling between the structure, mooring system (if applicable), foundation and surrounding soil(s). At the time of writing this is not possible for even a single device and instead global load analysis with boundary conditions is carried out to uncouple these interactions. For example, in most commercial mooring system packages the anchors are assumed to be fixed points. However, a coupled relationship may exist between the mooring line, anchor and surrounding geomaterials, particularly if partial or full failure of the anchor-soil interface occurs in-service. In this scenario any significant dynamic response of the anchoring point could in turn influence line and device dynamics. The complexity of this would be further compounded for shared anchoring points.

Several approaches to device, mooring and foundation system analyses have been introduced in this section. When selecting software package(s) or code(s) to carry out analyses it is important that the limitations in each are acknowledged and how any shortcomings may affect system design and performance, for example the factor of safety of identified components.

4 SECTOR SURVEY

4.1 VOC FINDINGS

As part of the mooring and foundation study a Voice of the Customer (VOC) survey was created to gather the opinions of the sector on current mooring technology.

The objective of the VOC survey is to understand the requirements of the sector. For instance, the VOC survey will provide an insight into such requirements as water depth, footprint, device excursion and anchoring preference for a given scale of machine. This will also help identify and understand sector perception of technical and economic challenges and highlight opportunities and requirements for innovation, which can be evaluated further as part of this work. The questions have been tailored to help confirm competing design requirements and contradictions, which is an also important aspect of innovation work being conducted under TRIZ. Some of the questions have been specifically tailored to the overlapping requirements with WES Cost Reduction in Supporting Infrastructure – Electrical Connection in terms of power export requirements, challenges which will help inform opportunities for innovation.

The survey was sent to 99 technology developers, including some from the wind and tidal sectors. It is acknowledged that some developers may have limited insight into mooring and foundation innovations being developed in the offshore sector. However, this Landscaping Report aims to highlight relevant aspects beyond the MRE sector.

This report summarises the responses to the survey and attempts to draw some pertinent conclusions thereon. The survey collected general information about the device before moving onto more detailed topics such as mooring requirements, environmental conditions and perceived state of the sector.

All the information provided by respondents in the survey has been treated as confidential. Therefore, throughout this report no mention is made to the names of persons, devices or companies which could be linked to any of the responses discussed.

4.2 THE SURVEY

The survey was split into 'tick-box' style multiple choice to collect 'information' and questions where a more descriptive response was requested to collect 'views', such as:

- *Have you encountered any key challenges addressed in the DESIGN of the mooring system including foundations and anchoring?*
- *Do you think the mooring technology required for an economically viable commercial scale deployment exist at this time? Please provide reasoning in the next question.*
- *Have you run into any challenges in the procurement, manufacture and installation of the mooring system for your device? Please provide a brief summary if you have.*
- *What do you see as the key moorings and foundations technical challenges the industry needs to solve to progress towards cost-effective wave energy conversion (marine energy conversion)?*

- *What do you see as some of the most significant risks in designing and deploying moorings and foundations for WECs (or MECs)?*
- *Do you see any significant knowledge or analysis gaps in the industry?*
- *If willing, please list your key suppliers of hardware and expertise in the field of moorings and foundations?*
- *Is your company working on any sub-system you view as being a technology enabler in the field of moorings and foundations (that you are willing to divulge)?*

This array of questions was designed to attempt to draw out key challenges thus far encountered by the sector in design and scale deployments and importantly understand how many MEC developers are working on novel technologies specifically related to moorings and foundations as it was the prior perception that a significant amount of sector effort is spent on these challenges.

For the 'data collection' type questions some justification for the question is given with the results below, where it is not immediately obvious.

4.3 Results

In this section results from the VOC survey are presented in graphical form and discussed. Unless otherwise specified the numeric labels on the pie charts and bar graphs refer to the number of respondents.

4.3.1 Overview of Respondents

The survey was sent to 99 Marine Energy Converter developers of whom the majority (70%) were WEC developers (Figure 29). It was decided to send to tidal (TEC) and floating offshore wind turbine (FOWT) developers in addition to WEC developers as many similar challenges are shared across the sectors and the potential for sector wide solutions is appreciated. The remaining 30% of requested respondents were split evenly between TEC and FOWT developers.

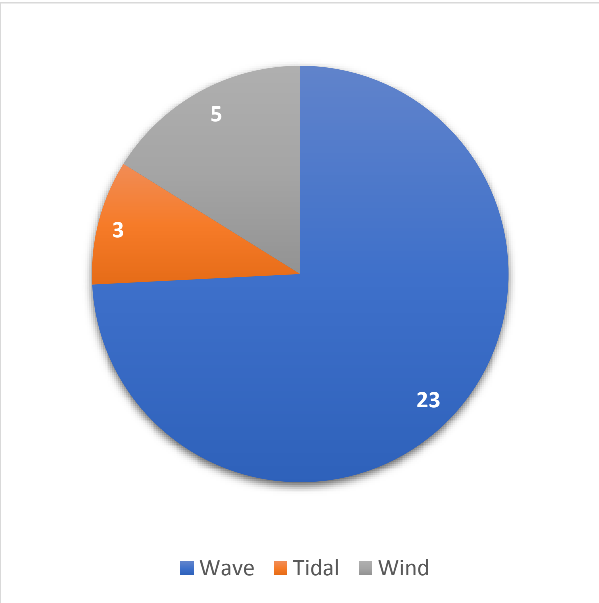


Figure 29: Sector of respondents.

4.3.2 Technology Readiness Level

Next, the developers were asked to specify their current Technology Readiness Level and the distribution is shown in Figure 30. This was partly to have information to 'temper' other responses. For example, if a TRL 1 developer states elsewhere that there are no challenges in the field of M&F then we could perhaps suggest that this developer has just not yet encountered the challenges yet. As it happens, more than three-quarters of developers place themselves in the 4 to 6 TRL range which is not unexpected with no respondents placing themselves at the earliest concept stages. As such we should have a reliable data set from experienced gamut of developers.

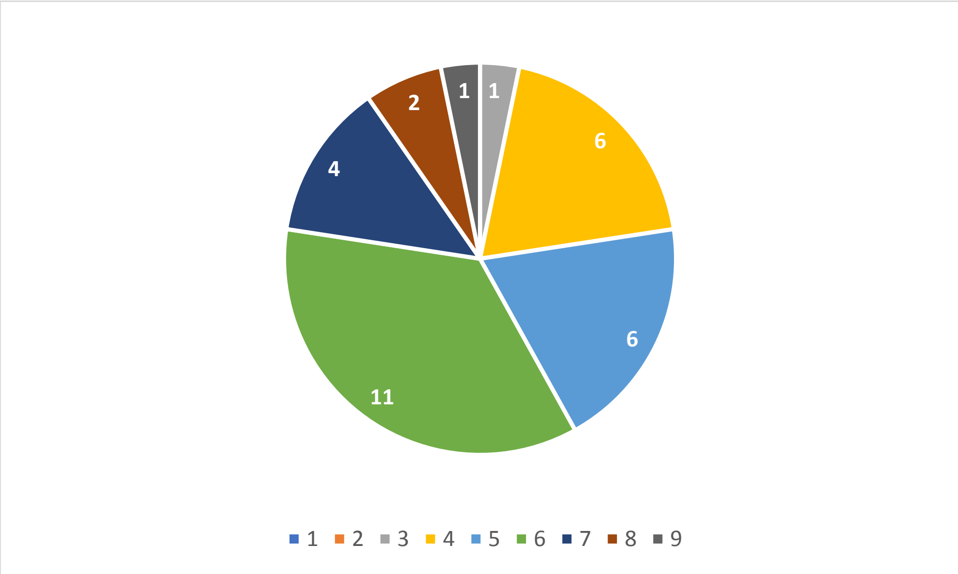


Figure 30: Technology Readiness Level of respondents.

4.3.3 Power Absorption Mode(s)

It is recognised that the WEC mooring system may have a positive or negative affect on device energy capture performance. These questions attempted to collate information of the device primary degrees of freedom (DoF) from which wave power is extracted. Figure 31 shows the distribution of DoFs used to extract power. The sum of data points is greater than the number of WEC developers who responded to the survey as some/many devices extract power in numerous modes/DoFs. Heave, surge and pitch dominate at this level and are roughly as common as each other.

This data set was analysed further for single-mode and multi-mode devices. Figure 32 shows that heave motion accounts for more than half of the single-mode devices. For multi-mode devices Figure 33 shows that power extraction from 2 and 3 DoFs cover the majority with only few devices claiming to extract power from greater number of DoFs and only 2 devices claiming power absorption from all DoFs. Figure 34 gives the occurrence of DoFs utilised for the multi-mode devices and this again shows that pitch, heave and surge are most common.

Later questions in the mooring system requirements section draw out the importance (or otherwise) of mooring system compliance on device motions. For example a single-mode heave device might desire a stiff vertical mooring tether for PTO ground-reaction whereas a multi-mode self-reacting device might desire a compliant mooring system to allow best device motions.

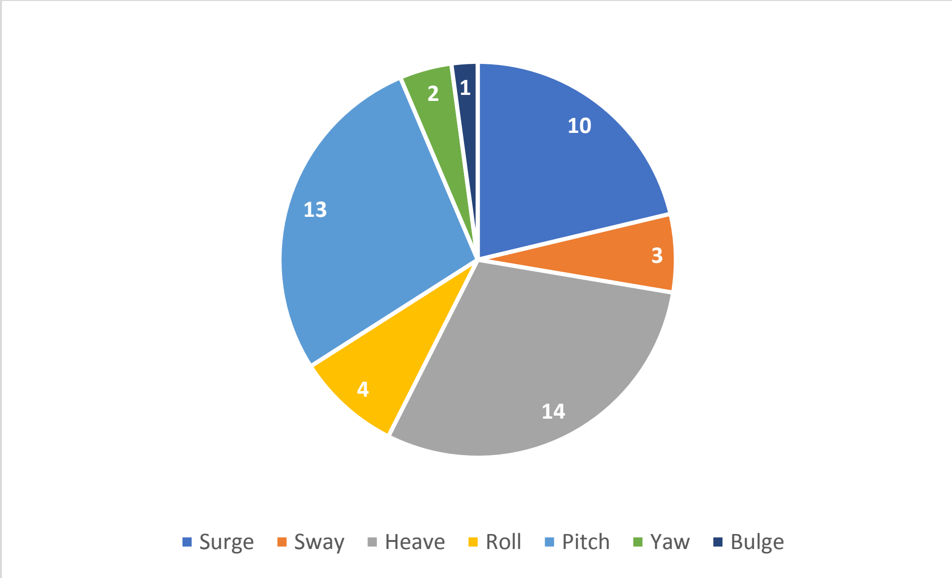


Figure 31: Power generating mode.

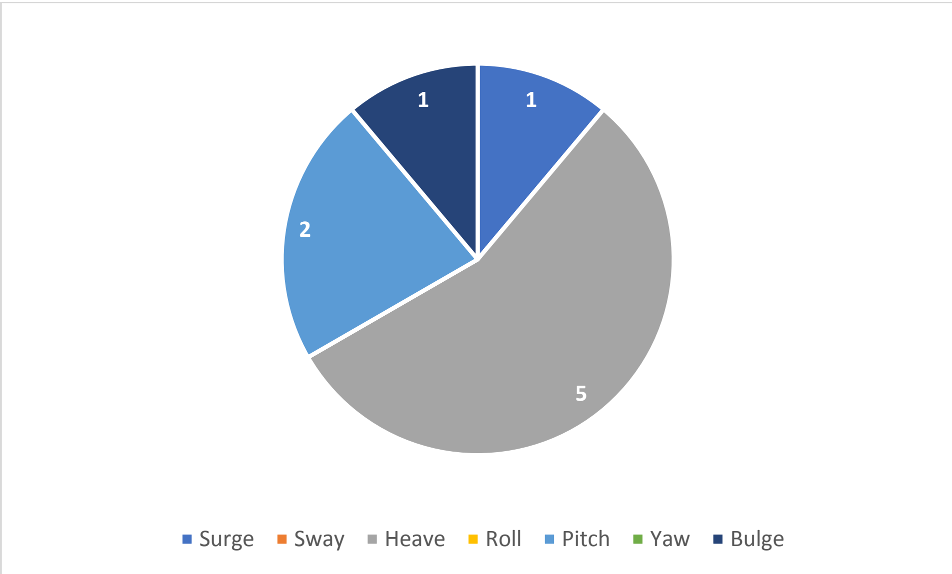


Figure 32: Power generating mode of single degree of freedom devices.

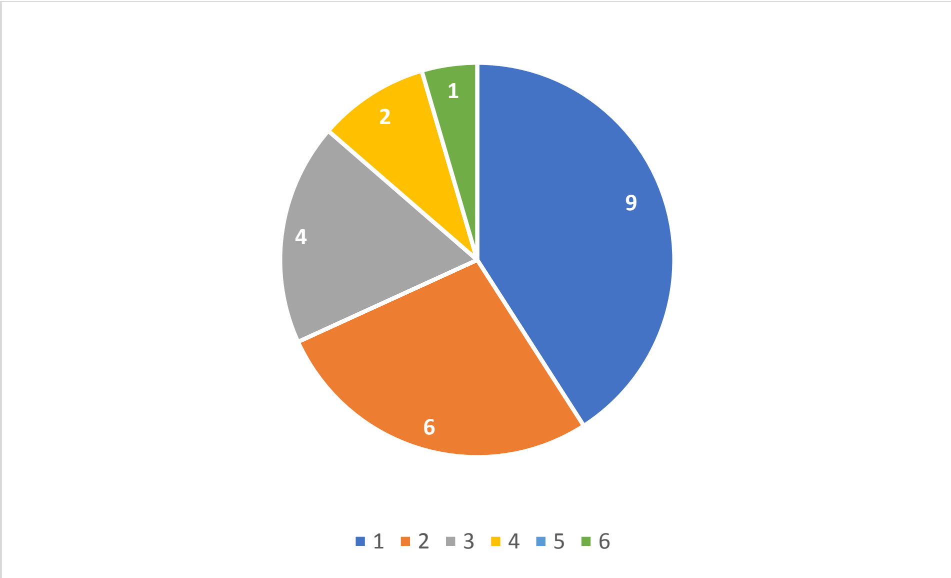


Figure 33: Number of degrees of freedom used for power generation per device.

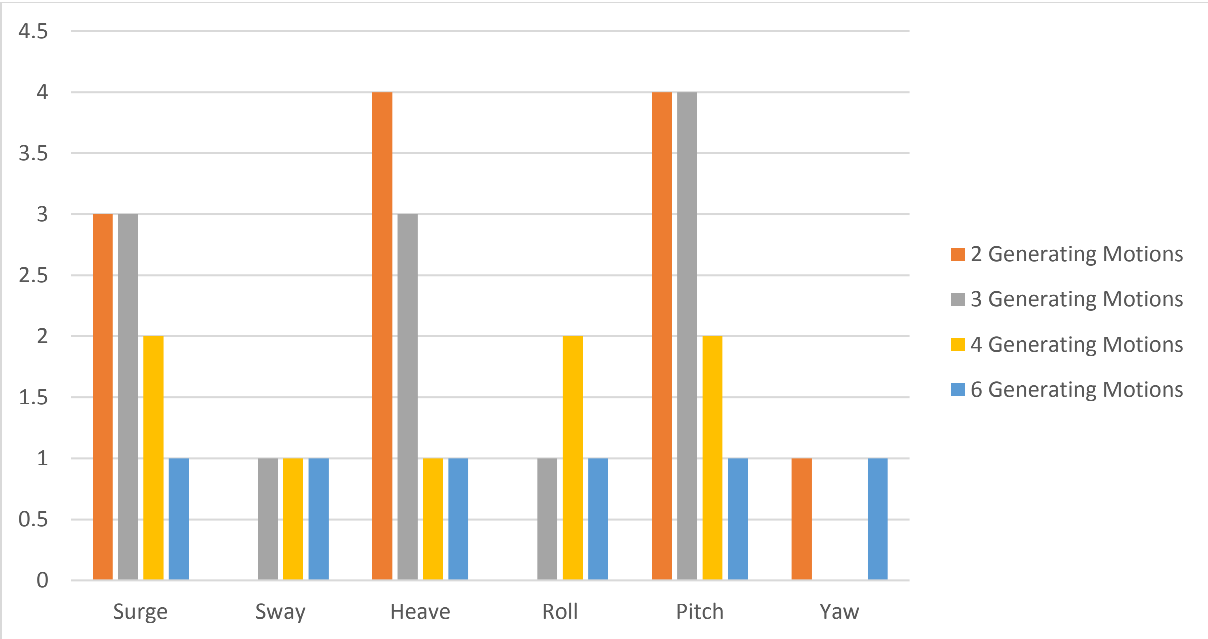


Figure 34: Occurrence of power generating mode for number of degrees of freedom per device.

4.3.4 Real-World Experience

Figure 35 shows the proportion of wave developers who have completed field trials of their WEC with around 65% having real-world experience. The range of scales at which these trials were conducted is shown in Figure 36. Test scales range from full-scale to one-fifteenth scale. It is acknowledged that the devices scales indicated by the respondants are specific to their device development plan and are not necessarily comparable between developers (i.e. the rated device power of a ½ scale device by 'Developer A' may be higher than the full-scale rated power of 'Developer B'). That being said, it is shown that the pool of respondents have accrued significant real-world experience at appreciable scale so their views are qualified and important.

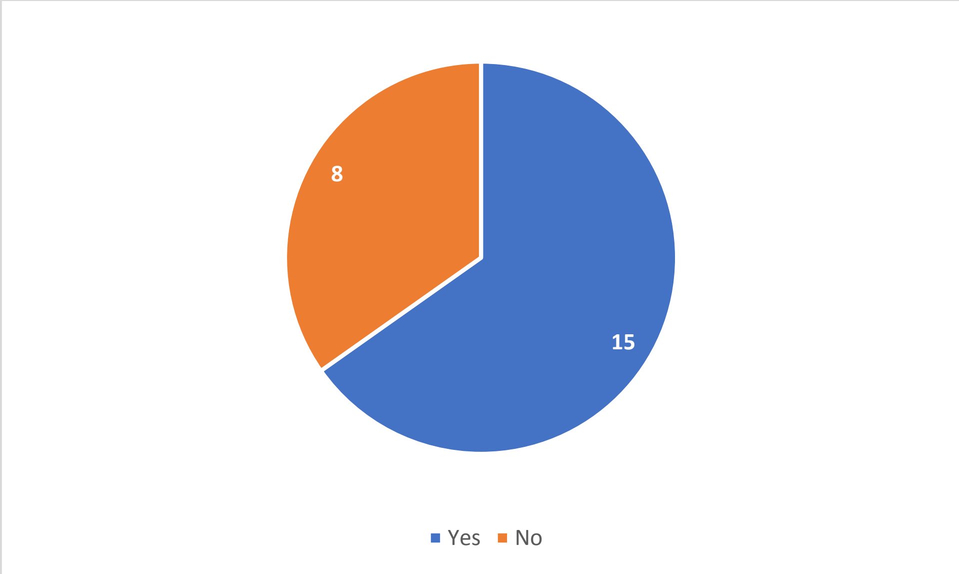


Figure 35: Proportion of WEC developers who have completed field trials.

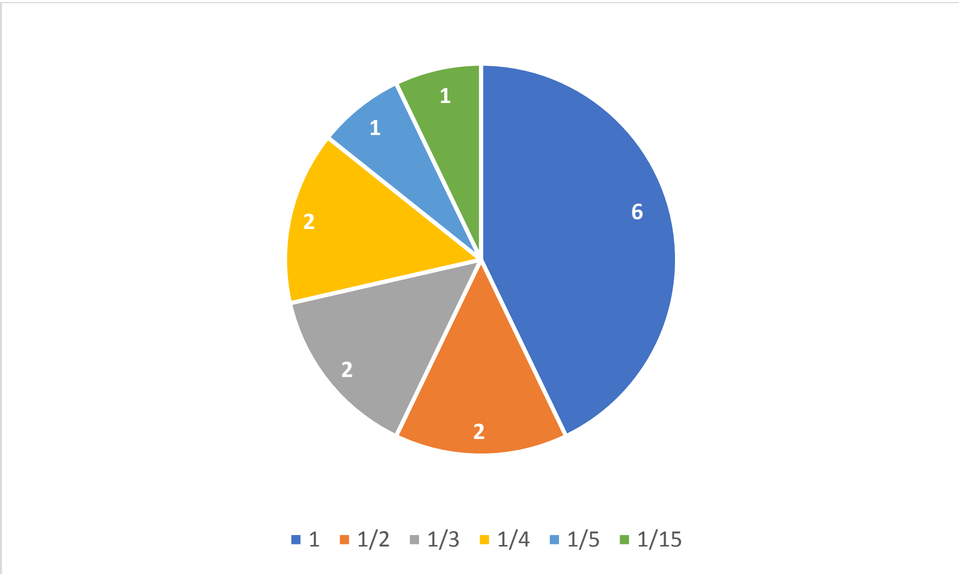


Figure 36: Scale of WEC field trials

4.3.5 Device Scale

Figure 37 shows a breakdown of the full-scale intent rated power provided in the responses from the wave energy developers. As shown the 100 to 500 kW range is the most significant but not extremely so with a very broad range of rated powers at full-scale. This gives an indication towards device magnitude (device magnitude *generally* increases with rating). It can be assumed that larger devices would attract more environmental loading and have highly loaded mooring and foundation systems as a result.

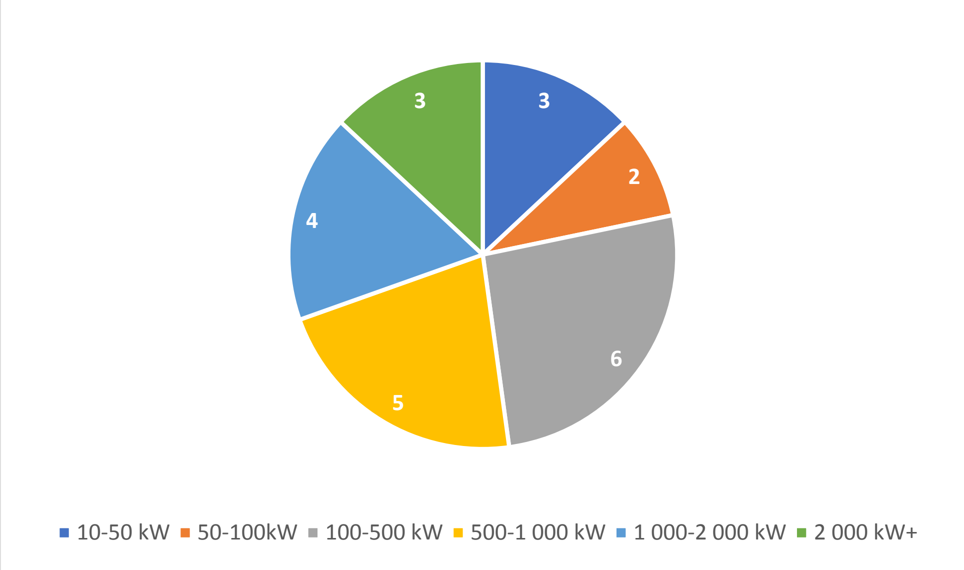


Figure 37: Rated power of WECs.

4.3.6 Power Take Off Load Path

A subset of WEC type exists whereby the Power Take Off (PTO) is located in the mooring load path (often ground-reacting devices). This is an important consideration for numerous reasons and Figure 38 shows that more than 75% of devices do not have this requirement. The remaining 25% therefore have this specific requirement which is an appreciable and important subset.

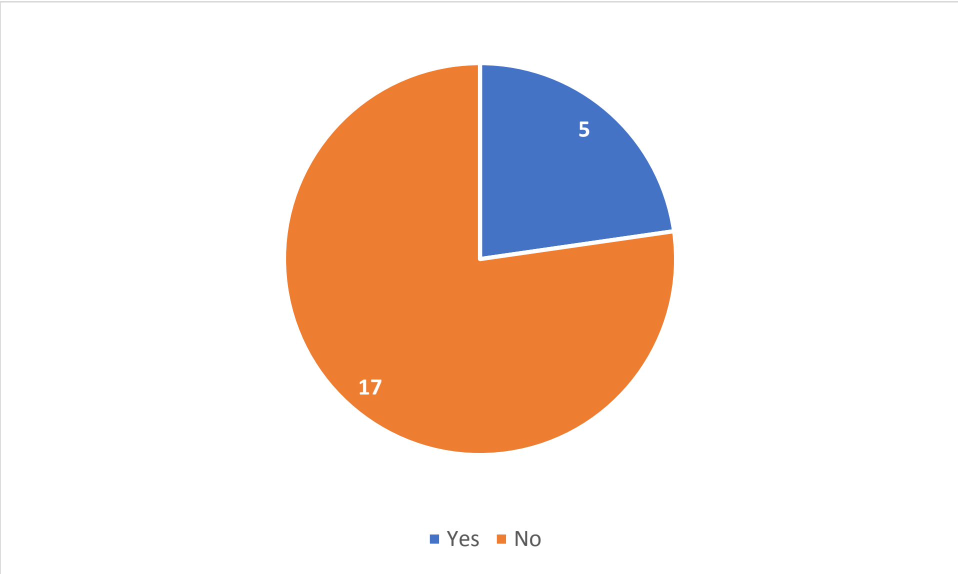


Figure 38: PTO located in the load path of the mooring system.

4.3.7 Active Moorings (for Survival)

A further subset of WEC type is those which actively adjust their moorings between operational and survival seastates, which leads to some interesting and bespoke mooring system design challenges such as application of control and actuation systems. This may be in the form of linear hydraulic (or pneumatic) actuators or winched systems (to change device position in the water column) or changing stiffness systems or other methods. This approach may be to minimise mooring system and structural loads or to maintain near-constant power generation across a range of seastates, or both. Figure 39 shows that 25% of WECs utilise this approach. Interestingly two developers 'don't know' which is surprising given it is a fairly fundamental early design decision. It can be perhaps taken as meaning, 'it is possible and we have not ruled this out at this stage' which would increase the proportion of this subset somewhat.

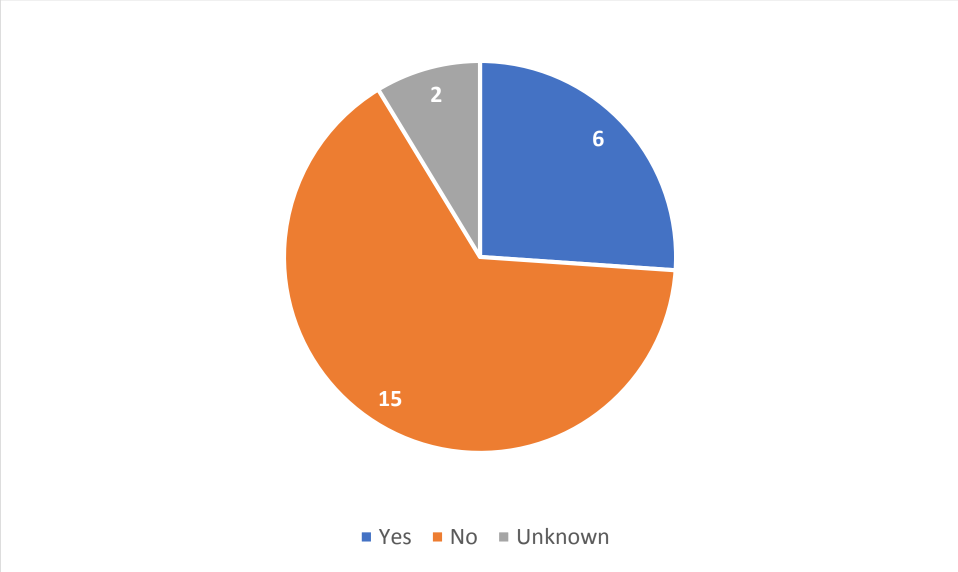


Figure 39: Active adjustment of mooring system between operational and survival conditions.

4.3.8 Design Environmental Conditions

Understanding the design environmental conditions is important for any mooring system design. This set of questions attempted to collate a view on the sector's design conditions. Some TEC and FOWT results are presented herein also for interest and context.

Wave

Figure 40 shows the range of significant wave heights against return periods corresponding to the design wave conditions used by the respondents. Further information on return periods can be found in Section 3.10.1. TEC and FOWT results are included. As shown the majority of developers utilise a 50 year or 100 year return period (yrp). It is suggested that a 1 year return is far too short for full-scale deployment analysis and 10 year return is also likely too short. The ranges of significant wave heights from 6 m to 16 m is also interesting and suggests that some developers are targeting more benign sites rather than high-energy sites, at least for initial phases of full-scale deployments.

As expected tidal developers have a lower design wave height but FOWT developers have the combined challenge of often exceedingly large devices and onerous design seastates leading to equally onerous mooring challenges.

Note: a 1-yrp significant wave height of 14m appears extreme but the point remains in the plot as Hs = 14m is not an unreasonable design wave. One erroneous data point of Hs = 28 m has been removed. It is likely this was a maximum wave height and may translate to a significant wave height of around 15m.

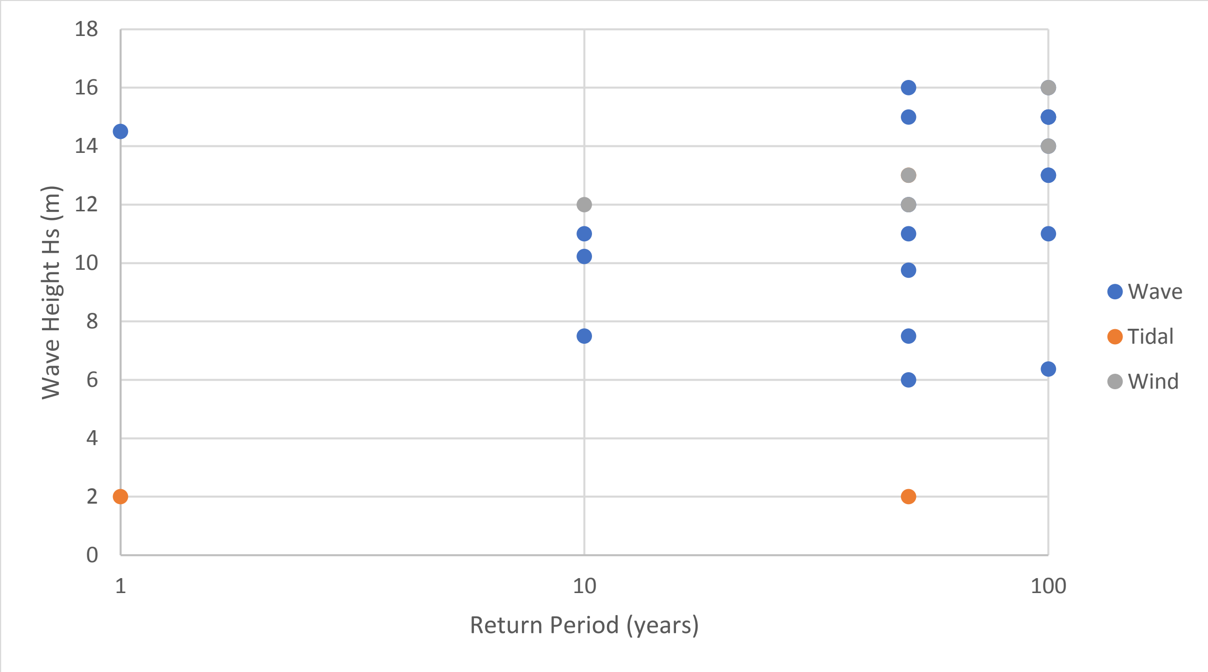


Figure 40: Return period and significant wave height of survival wave.

CURRENT

Figure 41 shows the distribution of design current velocities for WEC sites. Current is important as it can impart a significantly large quasi-steady force to the WEC, often unaligned with the predominant wave direction. Around half of the developers/sites have less than 1 m/s current (which is still considerable) and the remainder have greater current velocities which may be challenging. Current profile and return period were not requested in the survey.

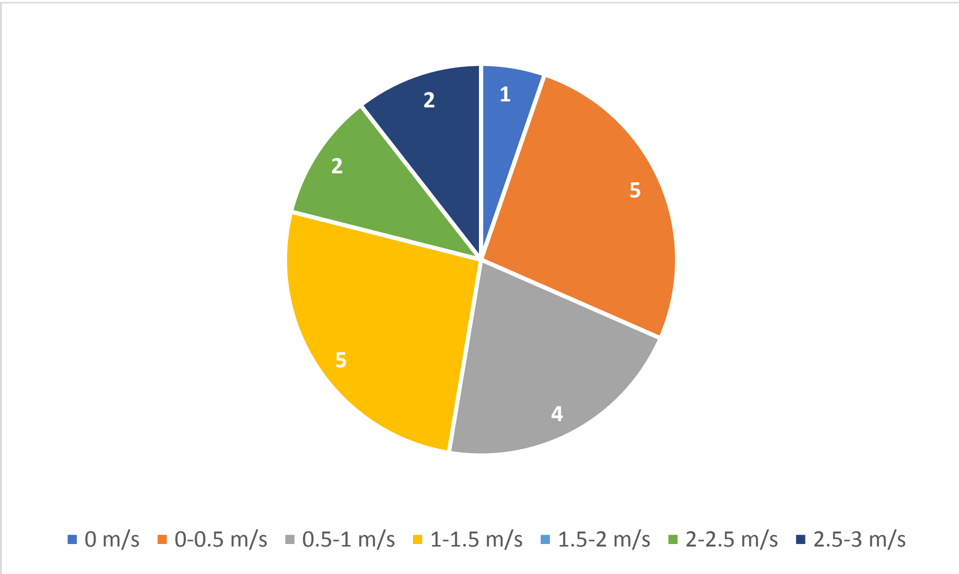


Figure 41: Design current speeds at wave energy sites.

WIND

Figure 42 shows the expected maximum wind velocities reported. For devices with freeboard wind can be an important quasi-steady force like current so it is important to consider in the design phases. The peak wind velocities are concordant with those expected for exposed WEC sites and the lower velocities probably correspond with those developers using a lower design wave height in more benign environments. The wind spectra, height above sea level, averaging period and return period were not requested in the survey.

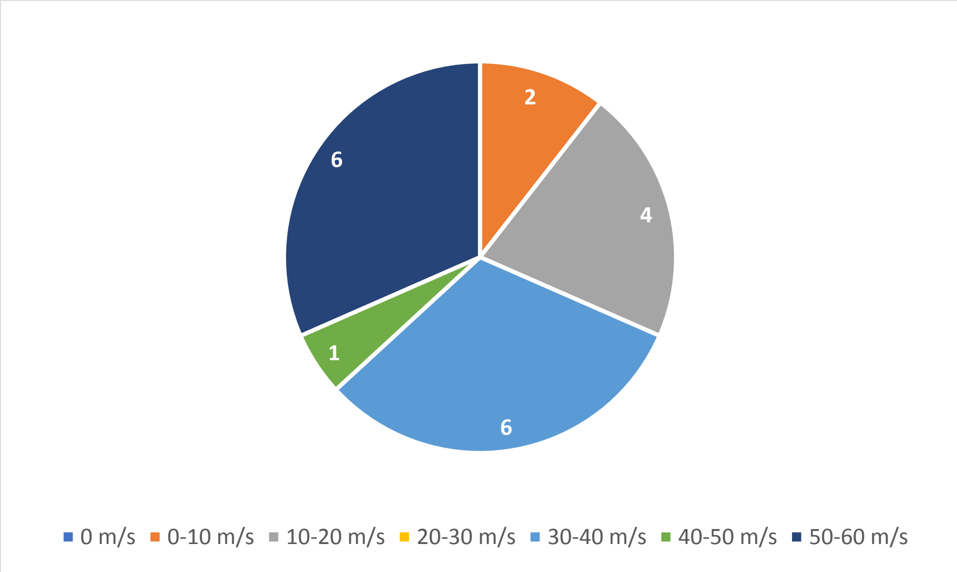


Figure 42: Design wind speed at wave energy sites.

WATER DEPTH

Water depth is important for mooring system design. Shallow waters increase the surge direction water particle motion which leads to greater excursions or loads. Deeper waters necessitate greater lengths of mooring line to reach the seabed but the deep-water waves may allow comparatively smaller footprints and may afford 'better' seabed conditions for anchoring/foundations. Figure 43 shows that 80% of devices target water depths of less than 100 m. If we define intermediate water depth as 50 to 100 m this covers 50% of devices. Only one device is targeting deep-water at greater than 150 m depth.

Figure 44 and Figure 45 show the same responses for wind and tidal devices. With only two data points it is difficult to draw meaningful conclusions for tidal devices but it would not be surprising that they generally target shallower waters. Equally it is unsurprising that large FOWT installations would target deeper waters.

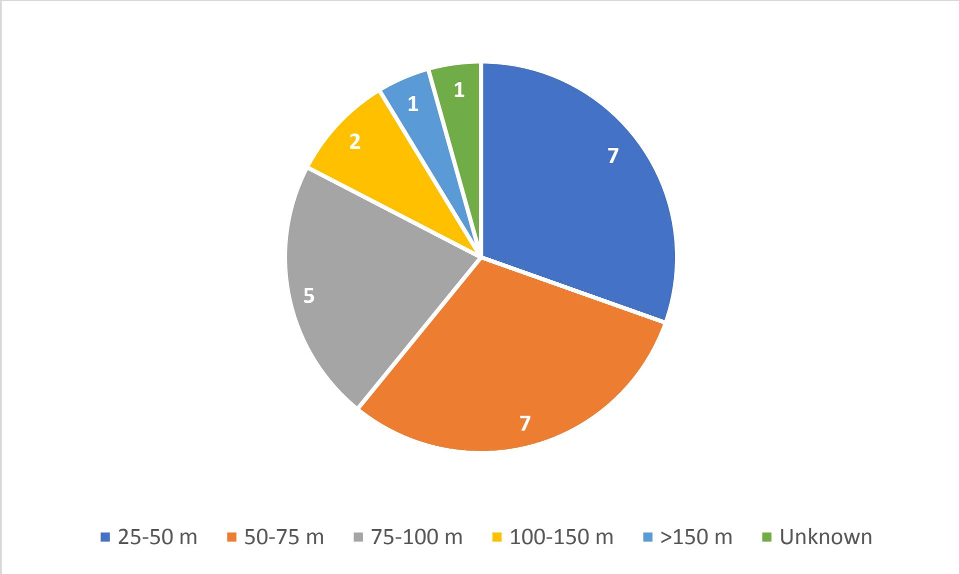


Figure 43: Expected water depth for commercial scale WECs.

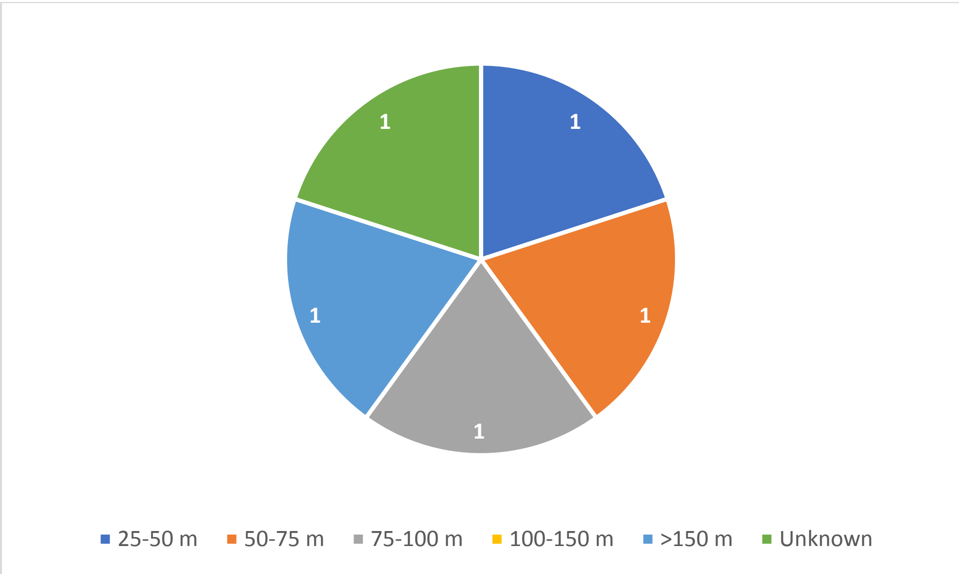


Figure 44: Expected water depth for commercial scale wind devices.

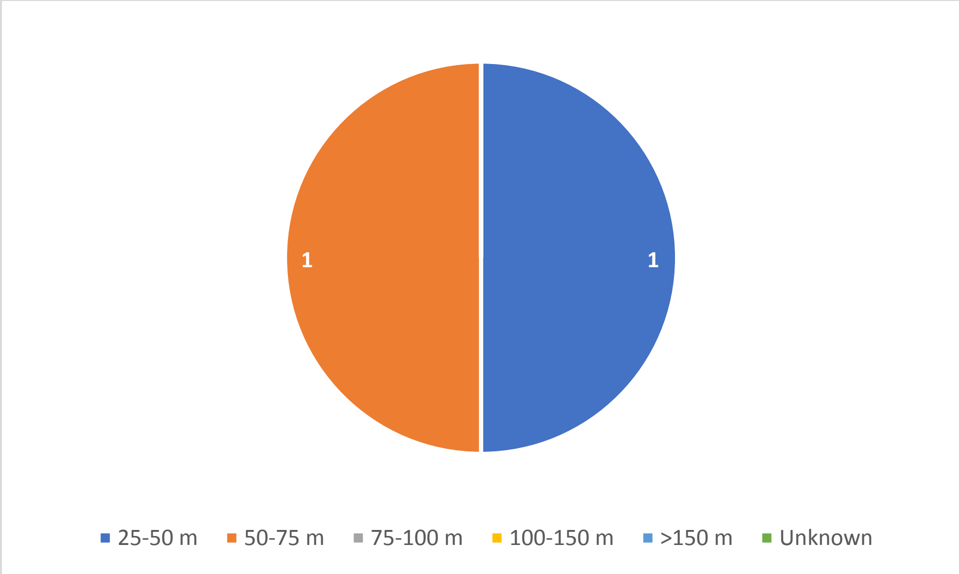


Figure 45: Expected water depth for commercial scale tidal devices.

4.3.9 Seabed Conditions

Seabed conditions (specifically geology) are one of the primary driving factors in the selection of anchors for the mooring system and are therefore important to understand. The geology at the anchors has profound effect on the anchor type selected and this in turn can have significant cost implications. Figure 46 shows the distribution of expected seabed conditions at a commercial scale WEC site. Around one-quarter of sites report deep sediment which may be considered to be ideal for drag embedment anchors and a likely lowest-cost solution. Shallow sediment and mixed conditions are likely to be more technically and thus economically challenging.

There is a weak trend in the data that deeper water increases likelihood of deeper sediment being available and shallower water promoting mixed or rock conditions which is not unexpected. Wave and current velocities are lower at the seabed in deeper water and disturb sediment less and this is the likely reason for this.

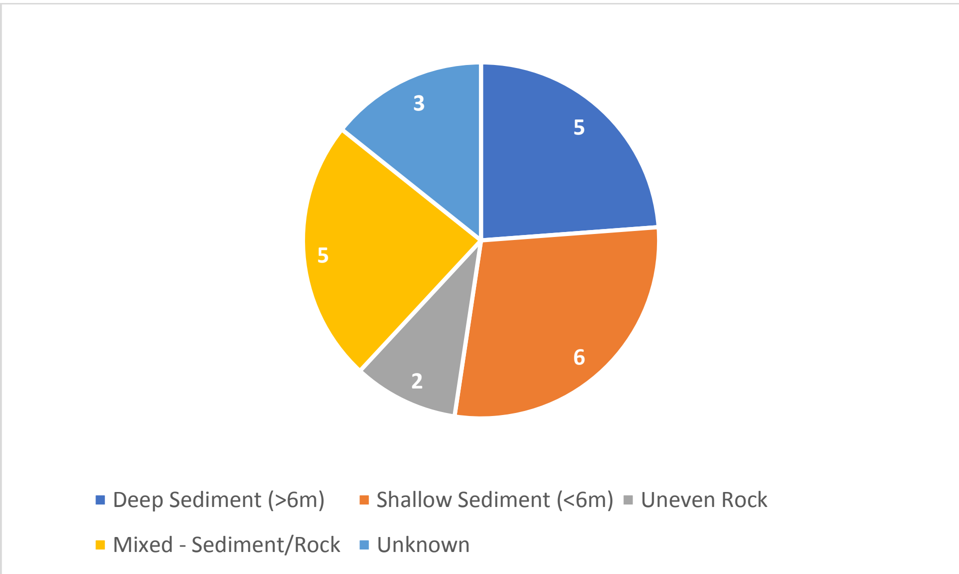


Figure 46: Seabed conditions for commercial scale WEC sites.

4.3.10 Mooring Footprint

The mooring footprint radius measures the distance from the device to the anchor point of the mooring system. A larger footprint allows for more horizontal compliance in a mooring system. Figure 47 through to Figure 49 show the reported mooring footprint for commercial scale deployments of wave, wind and tidal devices. As shown, for WECs, the range is considerable and relates to the device operation mode(s), scale, water depth, environment, seabed, mooring configuration and so on. The very small footprint layouts are likely to be single leg tether or TLP-type moorings, or similar, whereas the very large footprints are spread moorings. The cost interaction becomes complex as smaller footprints may have cheaper mooring systems but more expensive anchoring systems due to the presence of vertical load components at the seabed. FOWT installations report the largest footprints.

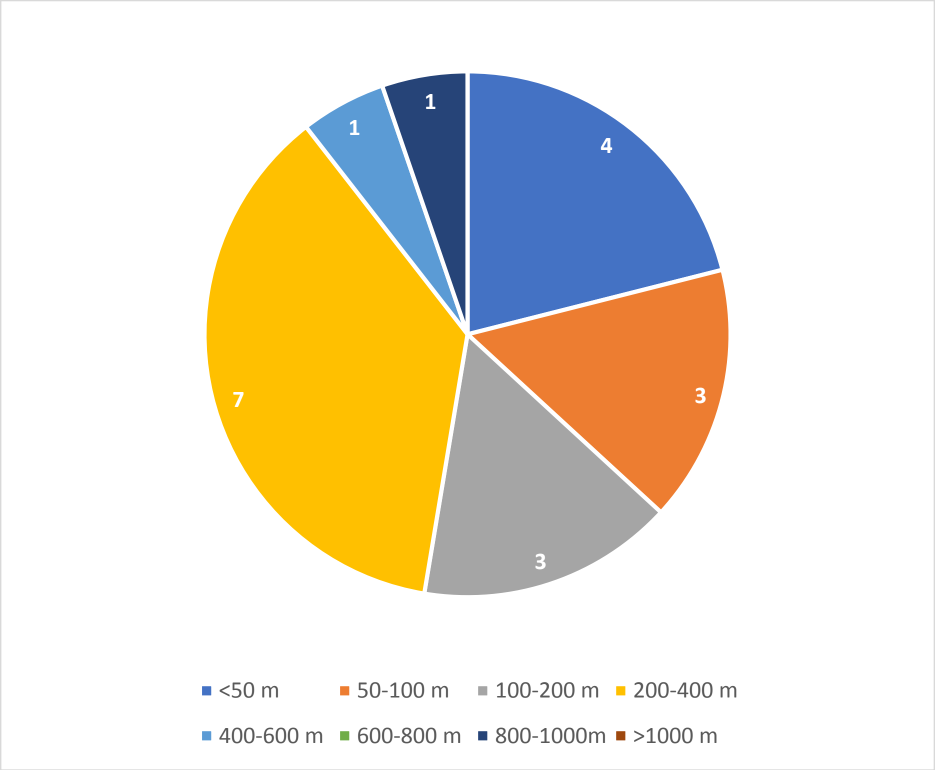


Figure 47: WEC mooring footprints.

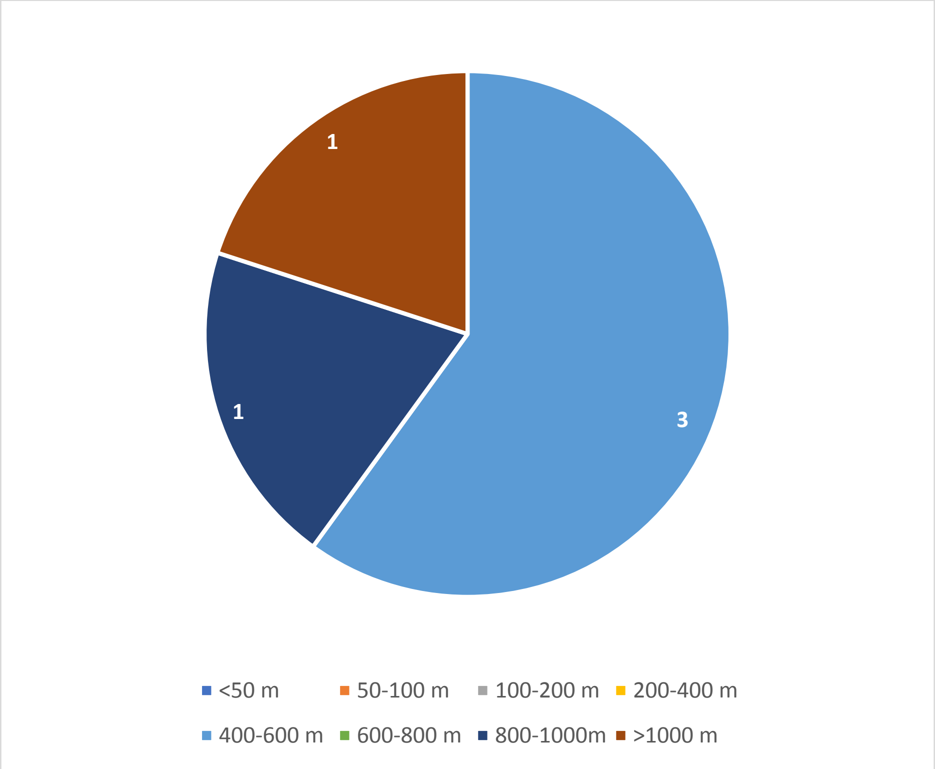


Figure 48: Floating wind turbine mooring footprints.

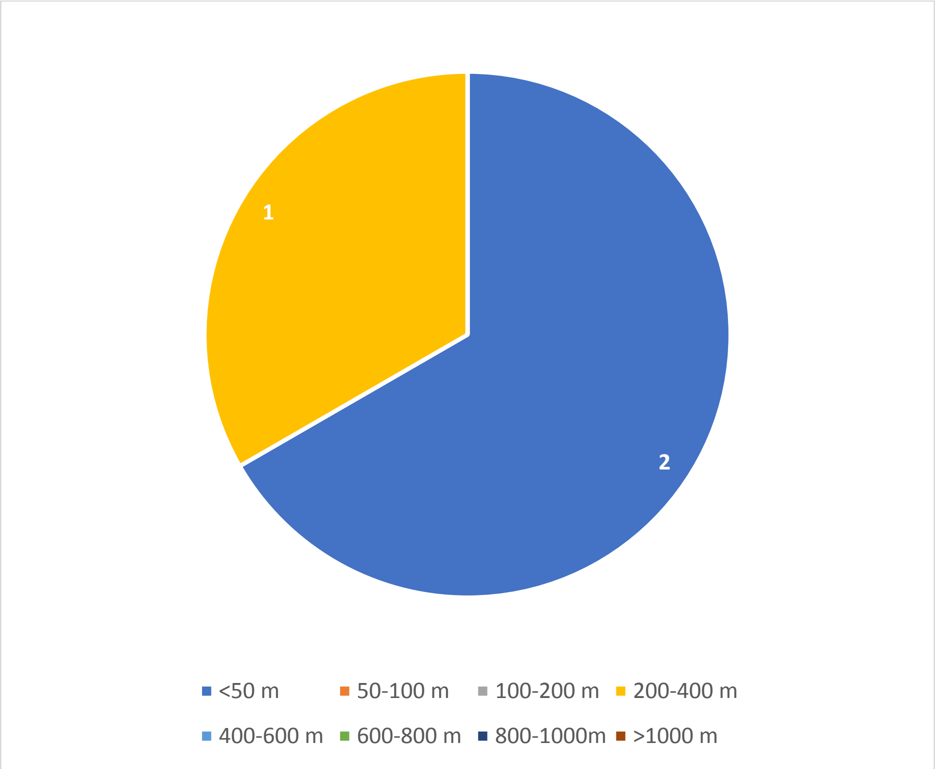


Figure 49: Tidal device mooring footprints.

4.3.11 Peak Line Tensions

Figure 50 shows the reported peak line tensions in the mooring system. A return period was not requested in the survey. These maximum line tensions are taken as being the maximum tension expected, or recorded, in the design survival sea state at the selected return period. The results are plotted against the rated power of each device. In the most general terms it could be expected that a higher-rated device would be larger and attract more loading to be reacted by the mooring system. This is not particularly evident in the reported data; with a very large device showing mooring line tensions which are lower than devices an order-of-magnitude smaller. Similarly, the range for a 3 MW FOWT device is very large. There is potential for mistakes or unit mix ups (kN, MN, tonne etc) in these responses and they need to be taken cautiously as a result.

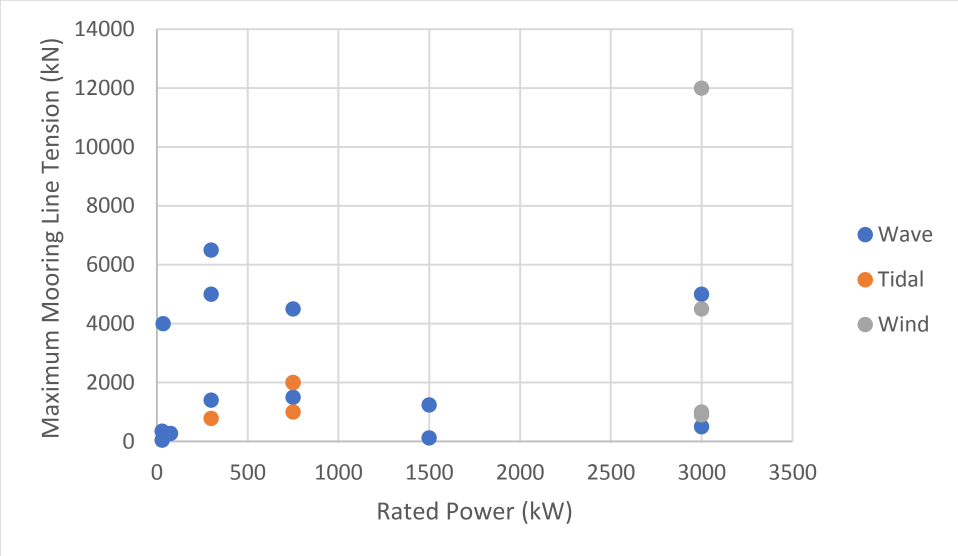


Figure 50: Maximum line tensions compared to device rated power.

4.3.12 Limit States

The survey asked which limit states developers were designing their mooring system to[22]. The majority (83%) responded that Ultimate Limit State was a design criterion. A smaller percentage also assessed Accidental Limit Stage and Fatigue Limit State (67% and 63% respectively). Fewer still (40%) considered Serviceability Limit State. Almost in all cases the limit states assessed were in a cascading fashion in the order of ULS, ALS, FLS and serviceability limit state (SLS). In other words a developer who examined ALS also examined ULS; one whom used FLS also examined ALS and ULS. One whom used SLS used all of the others so 40% of respondents assess all limit states in design. To some extent these results are a measure of whether developers are closely following typical offshore codes in their mooring design such as DNVGL-OS-E301 [4].

4.3.13 Device Horizontal Excursions

This question was deemed to be very interesting as we start to ‘drill-down’ into some of the conflicting requirements made of the mooring system. For example, a developer may wish to allow the device to move freely in surge to minimise mooring system loads and optimise power capture but must limit freedom to some extent to avoid clashing with other devices (array considerations) and mechanically overloading the electrical off-take cable (umbilical).

[22] Note: the survey participants were not asked which offshore codes they use.

Figure 51 shows that all of these considerations are important with umbilical design being the strongest, or most frequent, consideration. Interestingly power generation/capture is not shown as being a particularly strong or frequent requirement. It should be noted that reducing mooring loads and umbilical design requirements are likely counter to each other. A horizontally compliant mooring is likely required to reduce mooring system loads but this allows too much device excursion for successful umbilical design. So, with both of these aspects being required frequently we do see some important requirements contradictions beginning to appear from the sector.

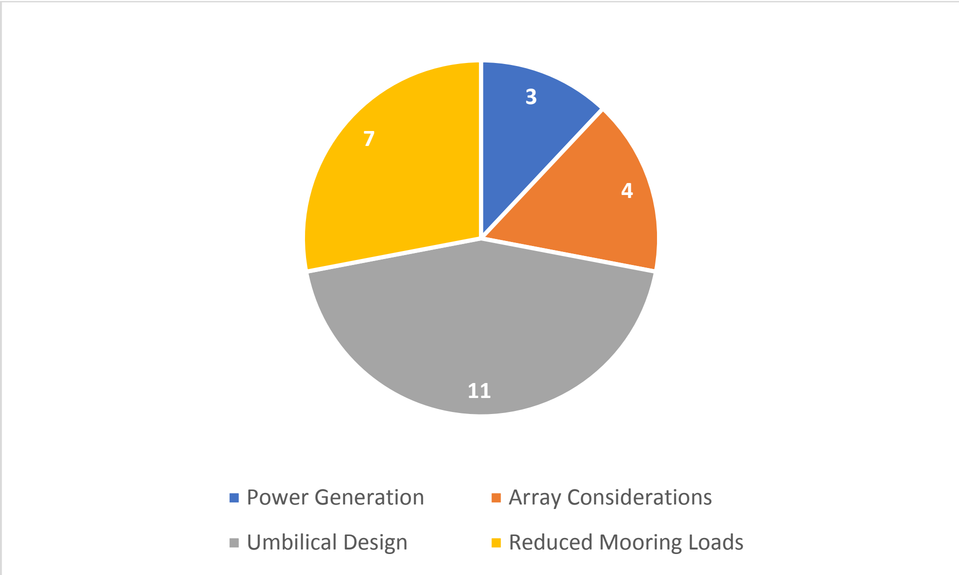


Figure 51: Considerations for limits to horizontal excursions.

4.3.14 Mooring System Type

Following on from excursion a range of mooring system types were offered in a menu for developers to select their design intent or preferred options. It was possible to select many types or all the types so there are more selections than number of respondents. The types available to select are shown in Table 11 schematically.

Table 11: Mooring system types provided for selection.

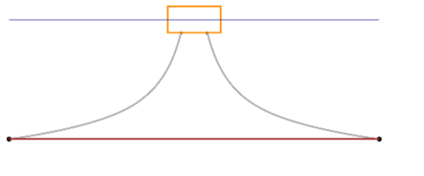
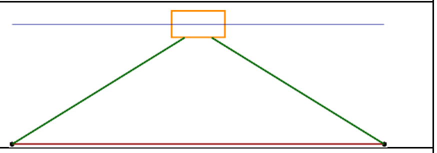
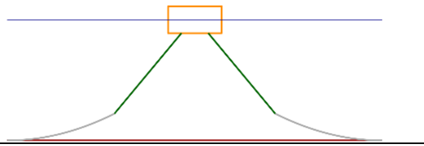
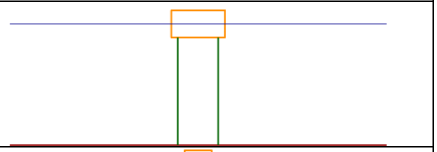
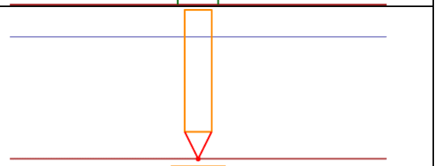
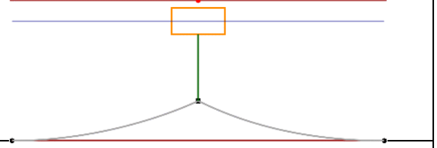
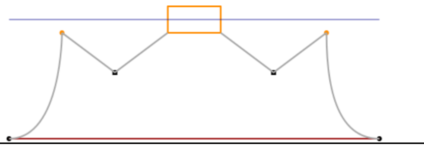
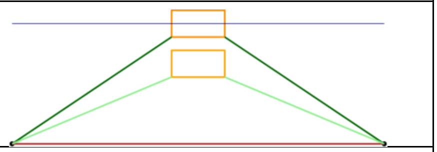
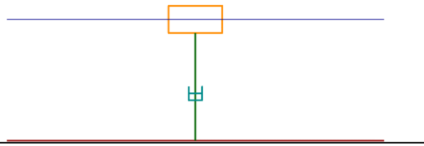
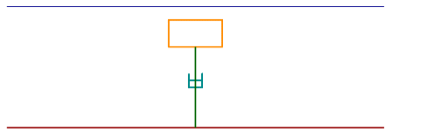
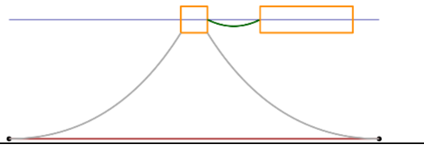
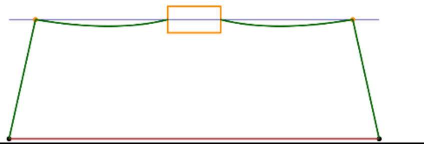
Catenary	
Taut	
Semi-taut	
Tension leg	
Articulated joint	
Admiralty	
Buoy-sinker ('W')	
Immersed survival	
Single line (WEC surface piercing)	
Single line (WEC not surface piercing)	
Single-point (SPM)	
Surface buoys	

Figure 52 shows the distribution of types selected. Clearly the full range has been deemed suitable by at least one developer and this depends on specific device types and designs. That being said 'conventional' catenary is deemed attractive for many developers being the most common response. Taut systems, semi-taut systems and variations of (e.g. buoy and sinker) are also important types. Note that most of the systems can be considered as hybrid mooring systems comprising both chain catenary and taut synthetic line elements.

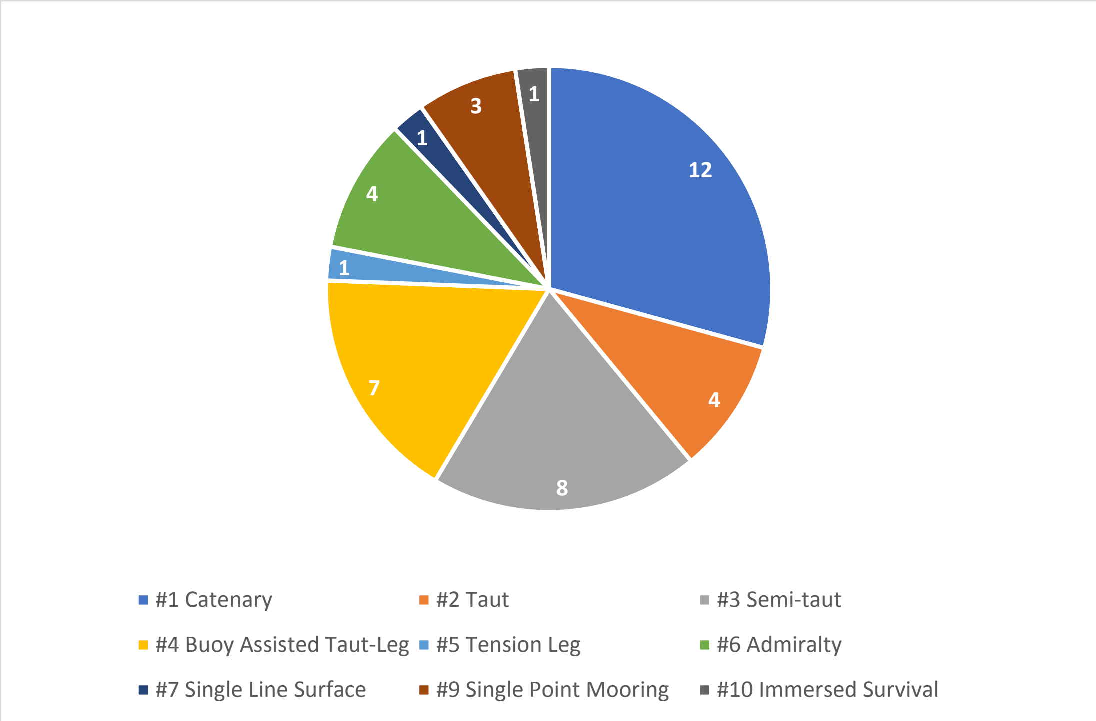


Figure 52: Considered mooring systems for WECs (see Table 11 for schematic descriptions of mooring system types).

4.3.15 Mooring System Sheaves

A subset of WEC device types are known to utilise sheaves (pulleys) in the mooring system and this question was designed to help understand how prevalent this subset may be as it carries with it some important characteristics and design challenges. Figure 53 shows that only three developers propose to utilise such a system but it is noted that four have not responded for some reason which may be either 'don't know' or 'do not wish to say'.

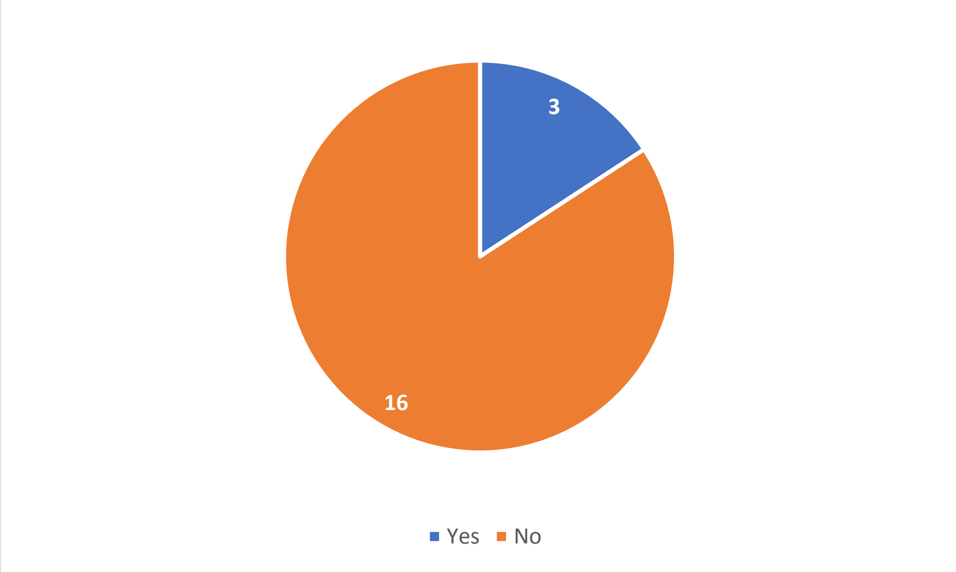


Figure 53: Mooring lines around sheaves (for WECs).

4.3.16 Mooring System Design Life

Figure 54 shows the desired or design intent lifespan of the components of the mooring system for WECs. More than half design for a lifespan of 15 years or greater which is typical for the design life of the farm/project and also many oil and gas type projects. Of course, shorter design lives cannot be precluded if it is shown to be economically viable/attractive to have cheaply replacement components or sub-systems.

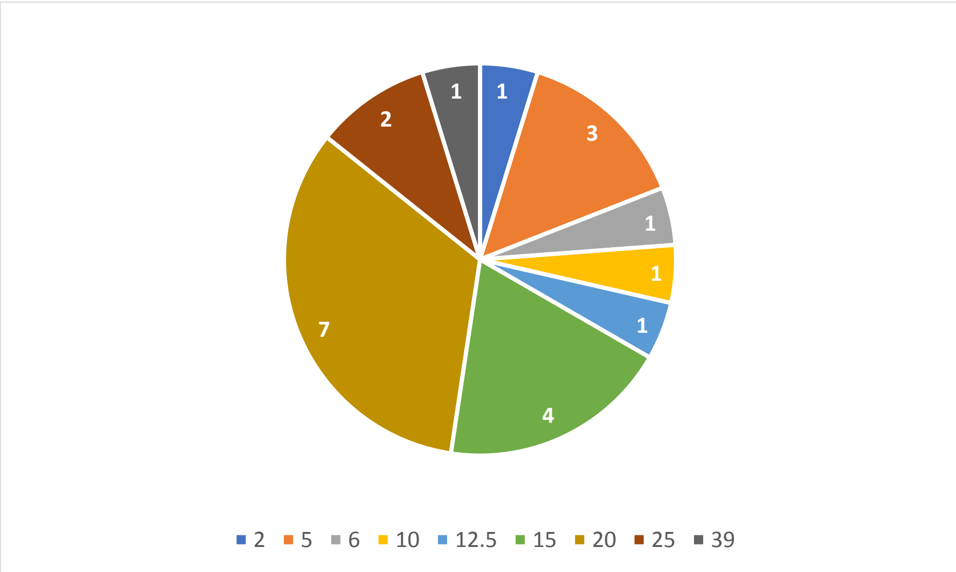


Figure 54: Expected lifespan (in years) of mooring line components (for WECs).

4.3.17 Mooring System Compliance

We have already touched on this important consideration to some extent when asking about device horizontal excursions. Here specifically it was attempted to investigate in more detail the desire for or against a 'compliant' mooring system and the reasons for this. Figure 55 shows that almost 40% of respondents do not require or do not want a compliant mooring system. Reduction of power production was a key reason for requiring compliance.

Almost 60% of respondents do want compliance to reduce the mooring system loads and loads transmitted into the WEC structure. These results show the vastly differing mooring system requirements for different developers. Only one WEC developer reported that compliance was required for power production reasons, which, as noted above, is a somewhat interesting finding.

The responses from wind and tidal developers all viewed compliance as a method of reducing the loads in the system.

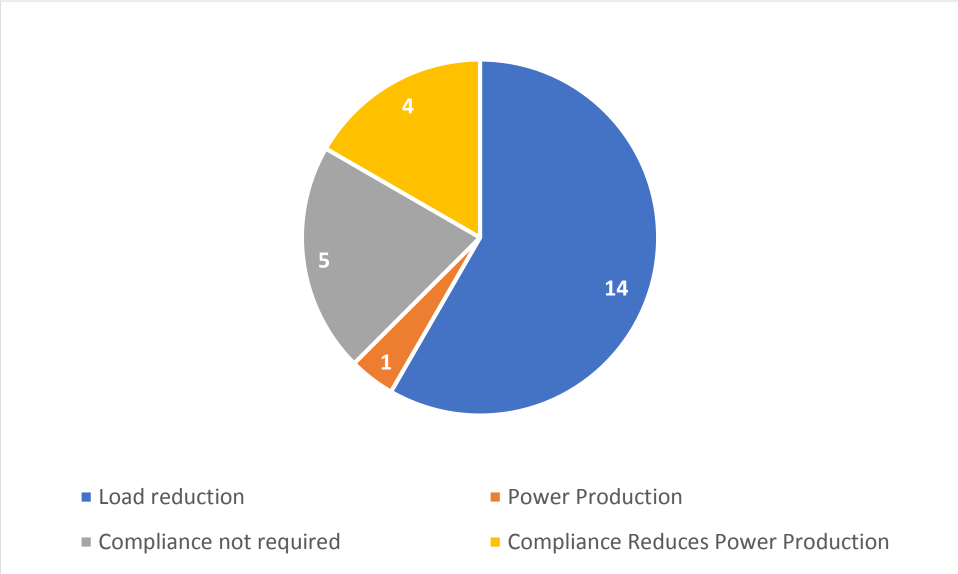


Figure 55: Impact of compliance on WEC device.

4.3.18 Mooring System Materials

This question aimed to collate the sector view on most appropriate materials in the mooring system components. Figure 56 shows that there is a strong uptake of synthetic fibre ropes for mooring lines but equally conventional steel chain remains popular. Steel dominates for connecting elements which is unsurprising. These results are essentially commensurate with offshore oil and gas solutions in common use and therefore do not show much innovative uptake by the WEC sector. A smaller group of developers were interested in more innovative material solutions for connectors and lines. A reasonable number show interest in elastomeric lines which can be assumed to be extensible load-reduction sub-systems.

For the avoidance of doubt the intent and meaning of the material categories was:

Synthetic: meaning synthetic fibre (polymer) fibre ropes

Steel: meaning steel wire ropes or steel chains

Elastomeric: meaning either natural or synthetic elastomers, colloquially ‘rubbers’

Composite: meaning a polymer matrix with reinforcing fibres (e.g. FRP, GRP, CFRP)

Metal composite hybrid: meaning a fairly novel material system in WEC applications with a fibre-reinforced metal matrix structure (MMC) with polymer surfaces for abrasion resistance.

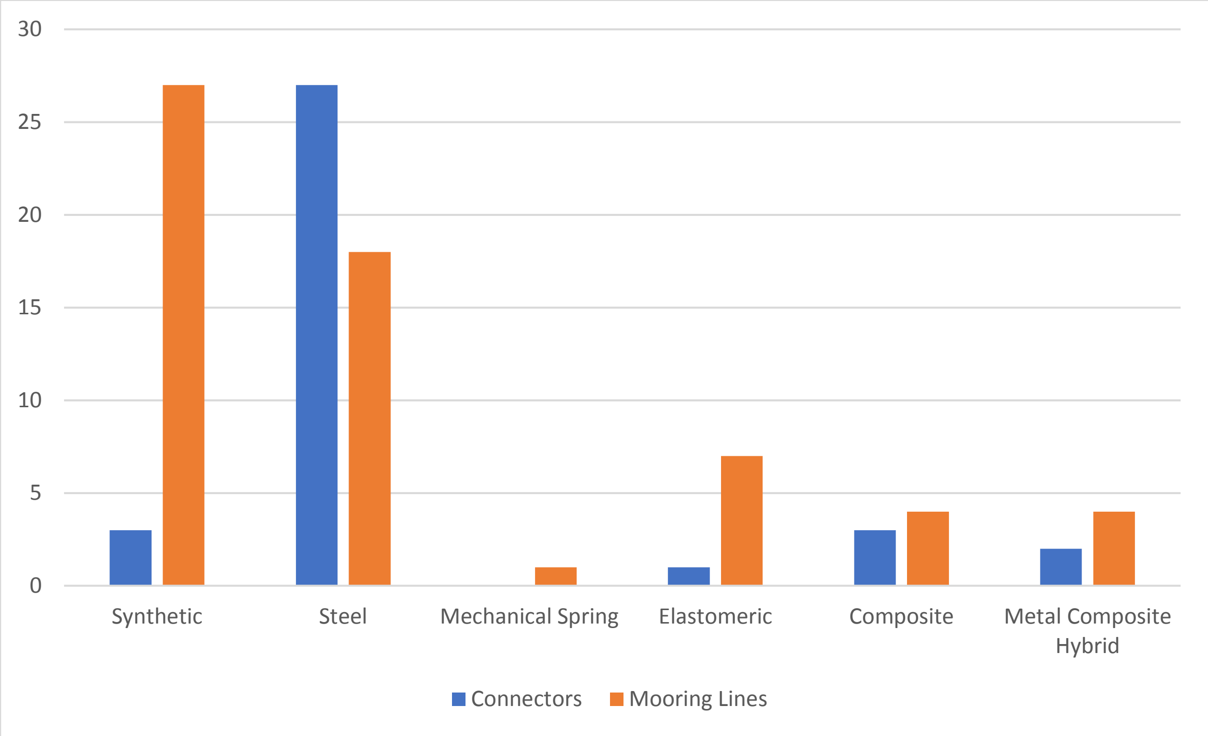


Figure 56: Uptake of mooring system materials.

Figure 57 shows the responses for desirable anchors types considered by the developers. Understandably (due to costs) drag embedment appears to be the most attractive solution. The range of other anchor types shows that developers understand that their specific site conditions may not allow drag anchors or their device imparts too much uplift at the anchor. Comments indicate that developers are open to any anchor type which technically performs as required at the lowest cost which is a prudent approach.

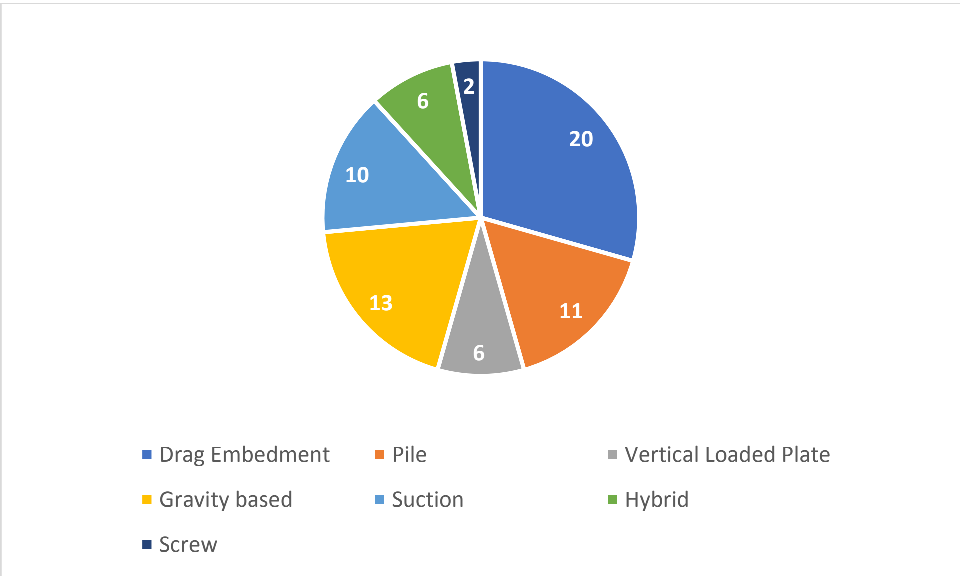


Figure 57: Considered anchors.

4.3.19 Weather Vaning

Figure 58 shows that 30% of devices require passive weather vaning and almost 10% require active weather vaning. Weather vaning is likely to be an important consideration for the design of the moorings and umbilical, and how they interact and may be an onerous challenge.

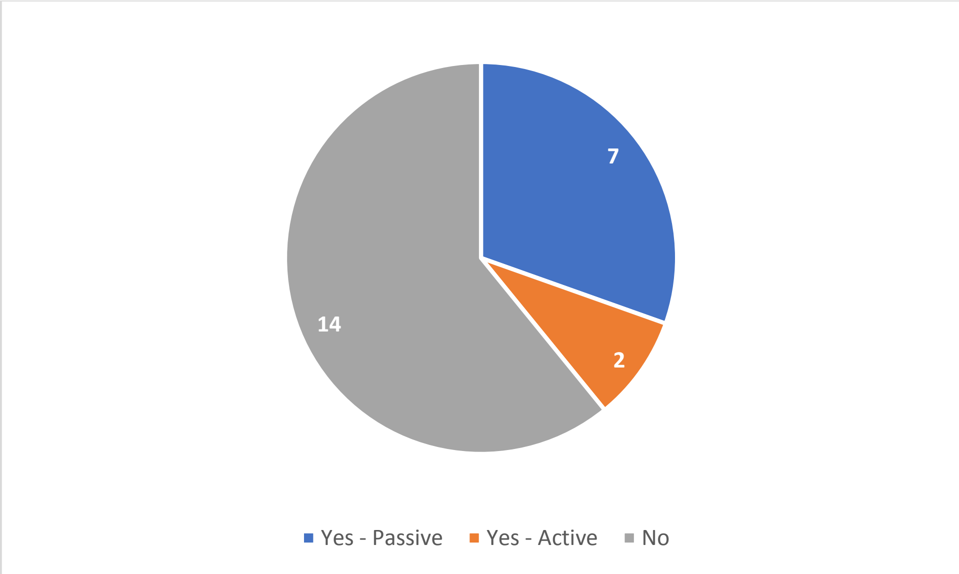


Figure 58: Device requirement to weather vane (for WECs).

4.3.20 Electrical Umbilical Management

Two questions were asked on electrical umbilical management. This was partly to collect some data which may be beneficial or interesting to the WES Cost Reduction in Supporting Infrastructure – Electrical Connection project and also to capture any specific requirements for the mooring system based on the umbilical requirements. Figure 59 shows that almost 60% of respondents are content with dry-mate electrical connections. It can be assumed that the remainders desire a quick-connection for electrical conductors and mechanical load path. Figure 60 shows that around three-quarters of developers are considering a lazy-S or lazy wave umbilical off-take.

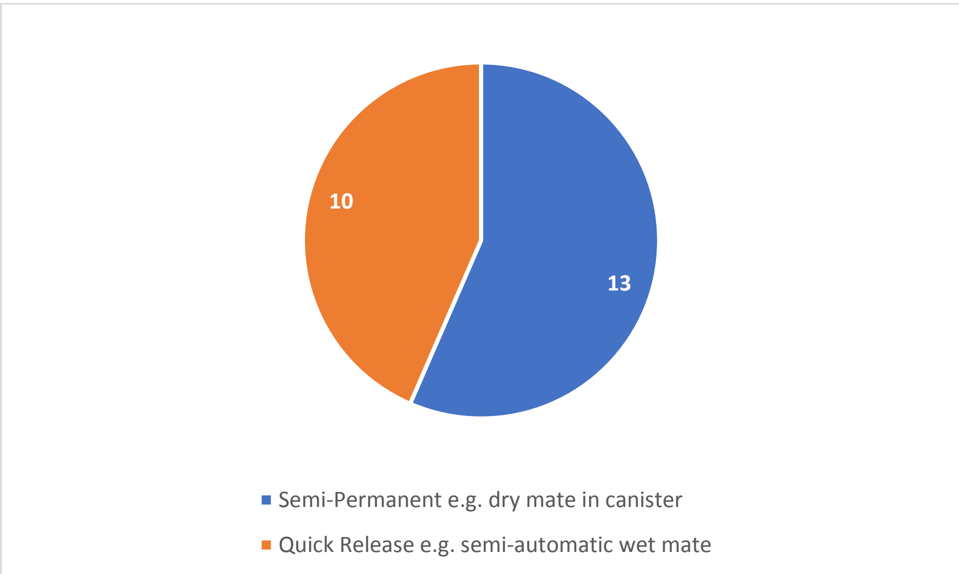


Figure 59: Umbilical connection type.

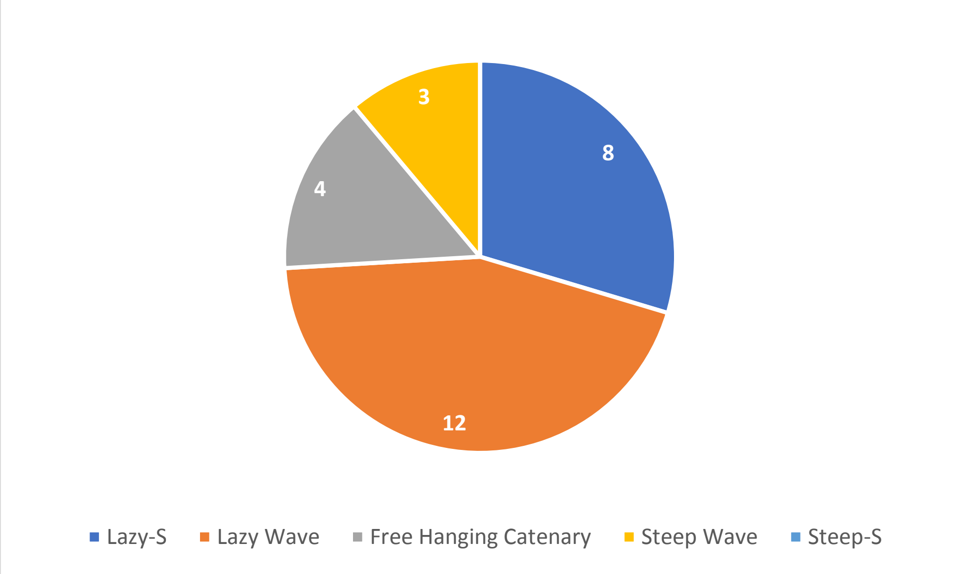


Figure 60: Umbilical design.

4.3.21 Infrastructure Sharing

The next three questions attempted to draw out how receptive the sector would be to 'sharing' infrastructure across multiple functions if a cost benefit was available by doing so. Figure 61 shows that around a third of respondents would consider mooring line sharing for an array of their devices. Figure 62 shows the same breakdown but for foundation sharing and this shows that even more would be open to this concept. The apparent acceptance of this concept is likely due to the fact that sharing anchors is conceptually straightforward and might be viewed as a low-risk step by the sector. Figure 63 shows that more than half of respondents would consider integrating the umbilical into the mooring system despite this being a fairly novel suggestion at this stage with no known commercial products which achieve this shared functionality. Three methods of achieving umbilical sharing with mooring 'line' are envisaged:

1. Utilise a mechanically strong umbilical as the mooring line. The single line provides power export and position mooring functionality. One method of achieving this could be to braid fibre rope elements around a fairly conventional power umbilical bore. Alternatively a conventional armoured electrical umbilical could be modified to incorporate enough strength elements to achieve the required mechanical properties.

2. Umbilical cable piggy-backed onto the mooring lines. A conventional mooring line and power export umbilical are utilised with some form of piggy-back clamp or fixture to attach the cable to the mooring line and the mooring line then defines the umbilical path through the water column.

3. For certain device types an inflexible tubular could be utilised as a mooring 'leg' (such an articulated joint and single-leg moorings in Table 11) and the electrical umbilical could be passed through this leg to exit at or near the sea bed and thus protecting the umbilical from the majority of hydrodynamic loads and motions.

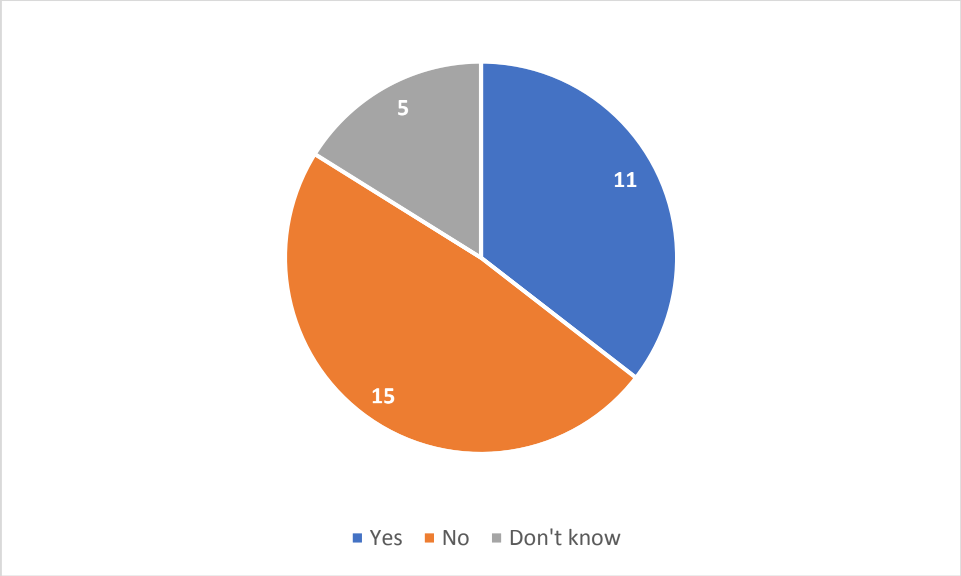


Figure 61: Mooring line sharing.

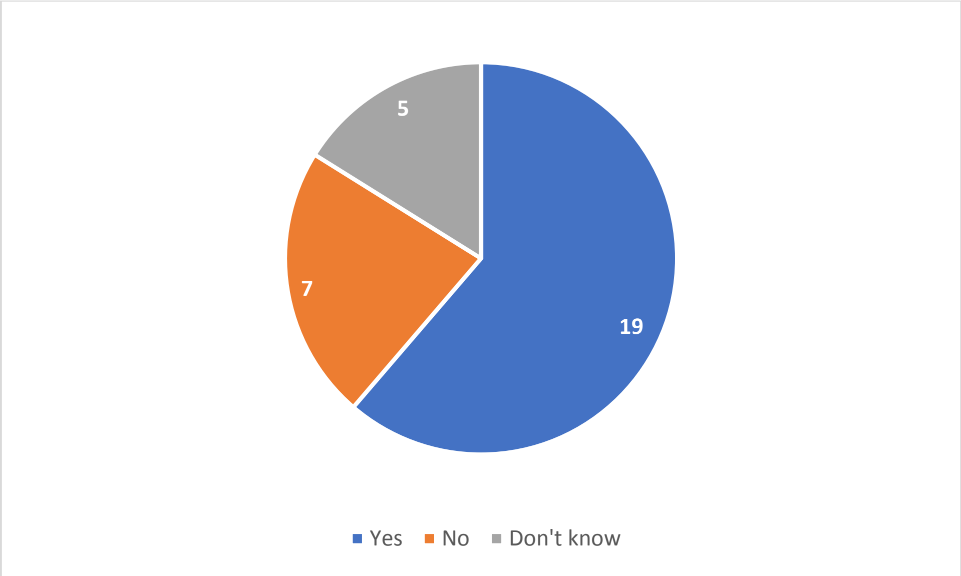


Figure 62: Foundation sharing.

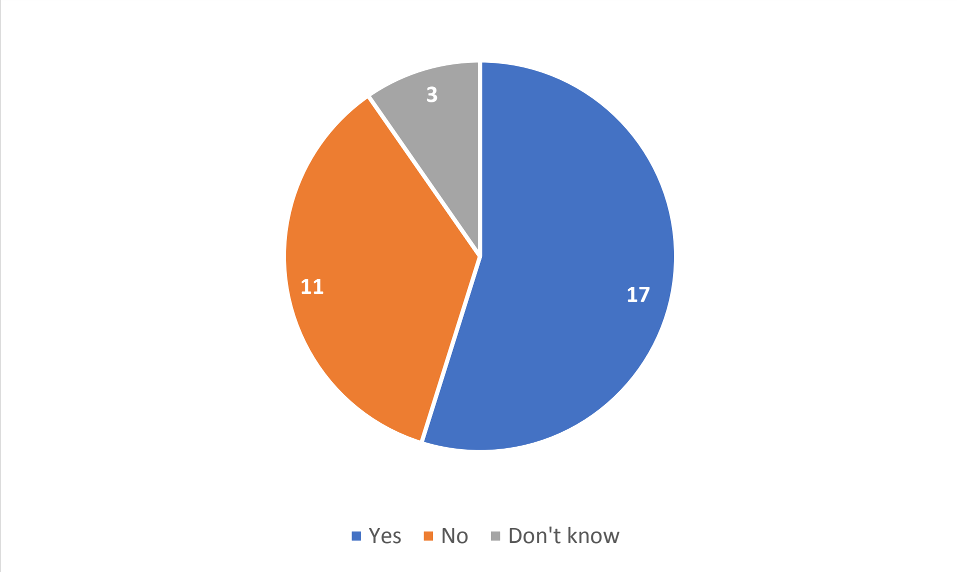


Figure 63: Consideration of integrating umbilical into the mooring system.

4.3.22 Marine Operations

The two questions focusing on marine operations attempted to draw out particular requirements for quick operations or operating in severe sea-states. Figure 64 shows that one-quarter of respondents desire hook-up within one hour and half desire hook-up within three hours. The remaining half allow more time for hook-ups but nearly all are within 'one-shift' and only three respondents allowing hook-up over twelve hours. For these it is assumed that these are the largest devices including FOWT and that 'safe-states' exist prior to the hook-up being fully completed. Figure 65 shows that more than 60% of developers accept an operations limiting sea state of 2 m which is typical. 30% desire operations in up to 3 m significant wave height and the remainder have exacting requirements for operations.

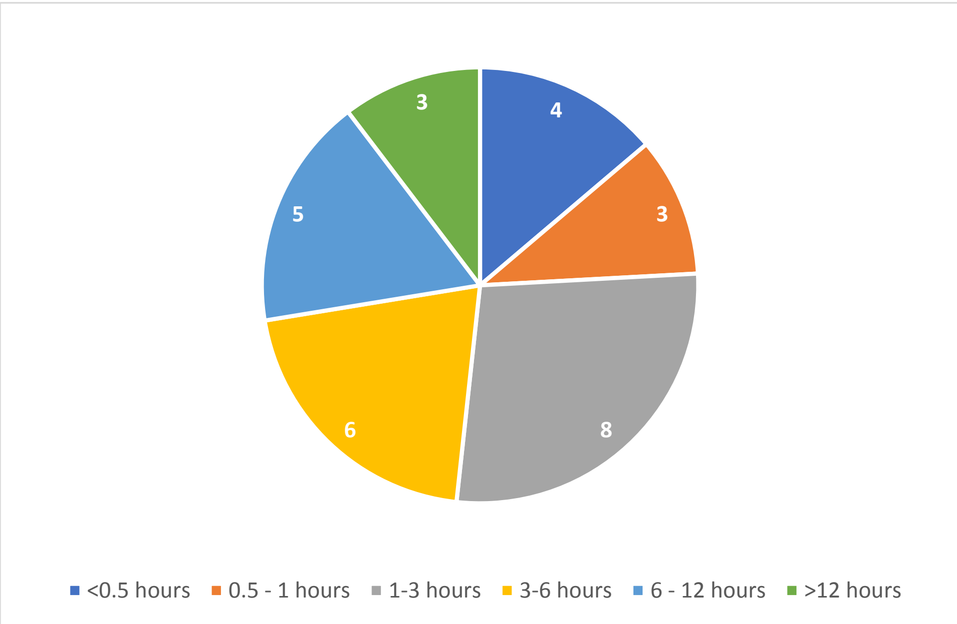


Figure 64: Anticipated device hook-up duration.

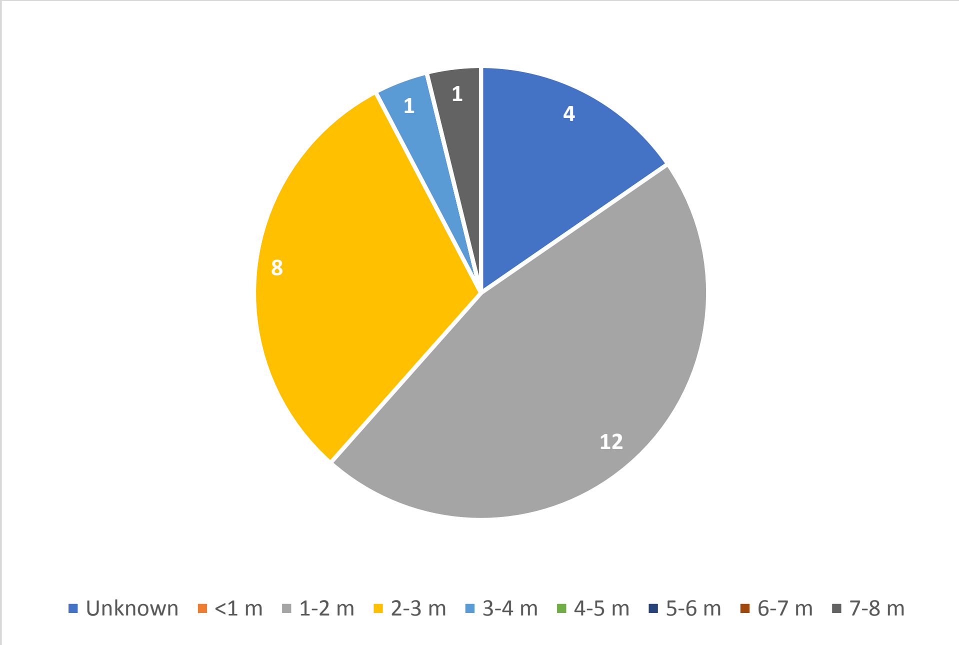


Figure 65: Limiting sea-states for marine operations.

4.4 VERBAL RESPONSES

The written responses to the questions aimed at collecting 'views' or insights is more difficult to summarise and present. Often very brief bullet point answers are provided or simply 'yes' or 'no' answers. As such, this section attempts to summarise the responses into a collection of 'yes' and 'no' and a list of pertinent bullet points. Global risks (to WEC sector development and industry in general), problems, challenges and issues are not reported herein as we are attempting to be specific to the mooring and foundation system. The section shall conclude by attempting to summarise briefly the key issues identified by the MEC developer network and any key development streams strongly identified by the developers are being enabling to the sector.

Only 16 respondents offered verbal answers and not all responded to all questions. Confidentiality restrictions were often cited.

Where specific responses are listed below additional commentary by TTI, in the way of analysis, comment or observation, follows on in parentheses with a "TTI:" precursor.

4.4.1 QUESTION 1

The question was:

> *Have you encountered any key challenges addressed in the DESIGN of the mooring system including foundations and anchoring?*

The primary outcome response to this question was resoundingly "Yes" with only one respondent saying "No". Some key trends began to appear with key challenges covering loads and motions, costs and anchor installation. The responses are summarised as:

- Balancing system strength with motion response of floating structure
- Making subsea connections between device and mooring system
- Fatigue and operations and maintenance
- High system stiffness requirement to minimise vessel motions
- Mooring lines must be suitable for winching (TTI: classically non-trivial with synthetic fibre ropes)
- Dynamic loading including snatch loading (TTI: frequent response)
- Assessing seabed coefficient of friction for gravity anchor design and holding capacity especially on rocky sea beds
- Challenge of how to best install numerous reliable foundations, quickly and at low cost
- Understanding of device RAOs challenging for traditional mooring designers (TTI: this is taken to mean that the more dynamic and non-linear response of WECs is unfamiliar to system designers more used to oil and gas installations thus leading to particular challenges)
- Load reduction combined with power cable design (TTI: this is taken to mean the contradiction already highlighted between allowing large excursions for mooring load reduction but needing to limit excursions for umbilical design and survivability)
- Large vertical loads (TTI: at anchors) is a challenge – both static and dynamic

- The contradicting requirements in the taut low-excursion system is challenging and requires detailed optimisation
- Cost and cost reduction
- Accurate description and representation of the load-elongation characteristics of synthetic fibre ropes
- Cost of foundation design for peak load level
- Foundation installation options
- Foundation design for cyclic and variable load
- Array layout for potential foundation sharing - operational and maintenance considerations
- Fatigue design for mooring lines
- Minimisation of weight of connectors, at seabed or mid-water
- Design of fuse technology for overload
- Design of active release system

4.4.2 QUESTION 2

The question was:

> *Do you think the mooring technology required for an economically viable commercial scale deployment exist at this time? Please provide reasoning in the next question.*

The general response here was more equivocal. There was an apparent belief or understanding that the technology required existed (and may be very conventional) but the coupled economic aspects of this were largely avoided. No strong evidence was offered that the existing solutions are economically viable and indeed it is intriguing that other questions state the costs of the system as being a challenge but this is generally not addressed in this question. Some of the responses were more globally concerned with the techno-economic viability of wave energy in general and these are not reported here as we are being specific to the mooring system. Only one respondent was wholly positive that the techno-economic solution already existed. Key responses included:

- A simple three-point catenary mooring system, or conventional/traditional/O&G type system, would suffice (TTI: however, this does avoid the economic aspects of the question. This was frequent response).
- Our mooring requirements are not too complex (TTI: therefore implicitly suggesting that they are techno-economically viable?).
- The products we require exist on the market (TTI: therefore implicitly suggesting that they are techno-economically viable?).
- Drilled solutions (TTI: assumedly anchor piles) are available today. However they are only economically viable in large quantities.

- Safety factors derived from O&G sector might be too conservative (TTI: implicitly suggesting that this will drive up cost unnecessarily. It is noted that different consequence classes exist but perhaps even lowest consequent class is still regarded as too onerous).
- Step-change improvements are required to reduce peak loads and footprint for WECs. New materials seem to be a promising alternative but reliability must be demonstrated.
- Lower-cost wet-mate (mechanical and electrical) quick connectors are required.
- Low-cost vertical load anchors required.
- Technology exists but need cost-reduction, through volume deployment (TTI: volume production need not reduce costs in this market).
- Prime-path is to adopt aquaculture type mooring systems which have seen developments and improvements and can utilise low-cost installation vessels.
- Techno-economic viability depends on automation and use of 'robots' and tooling.
- Our system is low-load for power rating so moorings are most cost-effective.
- Cannot be discussed without NDA in place.
- Cheaper compliant mooring systems are required to reduce loads in shallow water wave environment.

4.4.3 Question 3

The question was:

> *Have you run into any challenges in the procurement, manufacture and installation of the mooring system for your device? Please provide a brief summary if you have.*

Again a broad range of experiences were reported covering the entire range from "no" to "yes" with the caveat that many of the negative responses were "not yet" and therefore acknowledge the experience of problems depends on TRL and scale-deployment stage of the developer. For those who reported challenges they included:

- Issues with mooring lines (TTI: no further specifics so could be almost anything)
- Delays in development
- Local availability of suitable installation vessels and general cost and availability of installation vessel (TTI: frequent response)
- Generic problems related to overall sector performance (TTI: non-specific)
- No, but 90% of developers have a major challenge they haven't realised yet
- Post-tension of system following hook-up
- Cathodic isolation between device and mooring system
- See WES library
- Finding mooring lines (hawsers) with required stiffness

- Limited supply chain
- Yes, but discussion subject to NDA
- Willingness to work with synthetic fibres (TTI: unclear whose unwillingness; developer, supply chain, TPVs/certification societies, test sites)
- Wet-mate quick connectors excessively expensive for scale deployment. Less optimal solution selected for scale deployment as such.
- Relative costs for prototype installation are very expensive
- Long lead times
- Supply chain locations and sourcing and certification of components
- Unresponsible (sic) supply chain (TTI: no further specifics – assume meaning is 'irresponsible'… not known whether design supply chain or hardware supply chain)

4.4.4 Question 4

The question was:

> *What do you see as the key moorings and foundations technical challenges the industry needs to solve to progress towards cost-effective wave energy conversion (marine energy conversion)?*

Upon review the responses here began to become repetitive in nature as we have already asked about design and deployment challenges. Future perceived challenges are understandably based on the actual developer experiences to date. The pertinent responses included:

- Costs! CAPEX and OPEX
- Quick connect/disconnect
- Soil interface (TTI: assumedly anchor-sea bed interface)
- Avoiding high installation costs (product of vessel type and time; TTI: frequent response)
- Ensuring wear, fatigue and corrosion resistance is suitable (TTI: frequent response)
- Design tools including improved understanding of system response in shallow water depths
- Active mooring monitoring system
- Low-cost pile anchors in rock seabed in severe environment (TTI: could be generalised to low-cost vertical load anchors in all sea beds which is a frequent response)
- Peak loads
- Footprint reduction
- Mooring system design suitable for array configurations
- Minimisation of O&M costs (by targeting simple and robust systems requiring simple vessels to maintain)

- Class societies need to adapt requirements for sector (TTI: assumedly temper requirements compared with O&G basis in codes) including balancing cost and robustness requirements and Factor of Safety selection
- Avoid earth-reacting PTO systems (TTI: controversial!)
- Compatibility with fishing industry (TTI: and generalised to all stakeholder compatibility)
- Storm survival mitigation strategy
- Semi or fully-automated installation processes from the surface
- Impact of snap loading on fibre ropes (TTI: and rest of system)
- Smaller (TTI: assume lower mass, size) mooring jewellery (TTI: which is still) compliant with codes

4.4.5 Question 5

The question was:

> *What do you see as some of the most significant risks in designing and deploying moorings and foundations for WECs (or MECs)?*

Again, challenges begins to become somewhat synonymous with 'risks' so we see quite a lot of cross-over here. We also see the more global context of wave power extraction manifesting risks such as the environment and local sea bed conditions which is all reasonable. Some of the key responses included:

- Planning for failures which leads to redundancy which has a negative effect on system weight which can be detriment to performance (TTI: and cost)
- Fatigue
- Cost and risk of not finding economically viable solution within framework of existing classification society codes (TTI: frequent response)
- The environment (TTI: frequent)
- Power export umbilical design
- Vortex Induced Vibrations (VIV)
- Geotechnical details (TTI: frequent)
- Snatch loads
- Definition of most relevant design load cases
- Reliability of low-cost anchors in sediment and rocky sea beds
- Difficulty in mooring system monitoring leading to excessive factors of safety (TTI: and cost in turn)
- Weather windows for installation

- Third Party Verification (TTI: assumedly TPV increases development cost and can throw-up show-stoppers at late stage thus increasing cost to deploy)
- Single-point failures (TTI: lack of redundancy)
- Reliability of mooring lines and number off mooring lines
- Storm survival and mitigation
- Too much risk accepted on factors of safety (TTI: or more generally)
- Galvanic corrosion
- Mooring system design and development not concurrent with WEC development resulting in uncoupled design and late problems in deployment resulting in challenges and cost
- Lack of understanding in calculations (or overdesign due to uncertainties in analysis or model test)

4.4.6 Question 6

The question was:

Do you see any significant knowledge or analysis gaps in the industry?

Some, but not many, respondents did not see any significant knowledge or analysis gaps. Of those who did propose perceived gaps it must of course be recognised that they might be gaps in *their* knowledge (indeed one developer noted the Dunning-Kruger effect or "we don't know what we don't know"!) as opposed to gaps in the specialist mooring systems supply chain knowledge. Reported gaps included:

- Interested to see more work on synthetic compliant mooring systems
- Failure modes of mooring systems for intended application
- Influence of pitting corrosion on safe work load of mooring chain (TTI: reasonable as this is an oil and gas sector issue also and focus of some research currently)
- Coefficients of friction of different gravity anchor solutions on different sea beds (TTI: this is reasonable as available data is scant on this but the issue is it is such a specific issue it really needs site-specific data and ideally proof load testing of the actual anchor but recognised that this is difficult for design and minimising factors of safety)
- Oil and gas knowledge and experience not directly relatable which is what a lot of mooring system experience is based on
- Detailed geotechnical analysis of screw-in anchor piles specifically in sediment
- Long-term reliability and certification may be challenging due to knowledge gaps for solutions which may other be technically and economically attractive (TTI: assumedly more novel solutions where qualification basis does not currently exist)
- Not enough knowledge – still room for mooring line optimisation
- Mooring system component reliability

- Quick connect/disconnect
- Novel hull shape and configuration motion response uncertainties
- Real-world experience
- Comment: there may be gaps in developer knowledge but can be addressed by involving mooring system design experts as soon as possible in design programme

4.4.7 Question 7

The question was:

> *If willing, please list your key suppliers of hardware and expertise in the field of moorings and foundations?*

In general developers seemed reticent to answer this question which is surprising as a list of mooring equipment suppliers and design houses is hardly proprietary information which cannot be easily found. Of those who did reply the compiled list of suppliers was:

- AquaMoor
- Arcelormittal
- Asian Star
- Bexco
- Confidential
- Dae Yang
- GN rope fittings
- Hamanaka
- Hydrobond
- Hydro-Group
- In house designs
- Lankhorst
- Lavelle Boats
- Le Beon
- Leask
- Motive
- Nippon Chain
- Ramnas
- Seaflex
- Sotra
- Standard marine components
- Tension Technology International
- Trillo
- Tritec Marine
- Vicinay
- Vryhof

4.4.8 Question 8

The question was:

> *Is your company working on any sub-system you view as being a technology enabler in the field of moorings and foundations (that you are willing to divulge)?*

Again, and perhaps more expectedly, confidentially concerns were dominant here. Many respondents responded that they were working on enabling technologies but were not willing to divulge any details which is not unreasonable. Of the more specific responses systems for increasing (and controlling) the compliance of a mooring line was a common one as was quick connect and disconnect systems which shows that the sector has identified these areas as key technologies for solving important challenges. Of those willing to state their development areas the key ones were:

- Quick connect and disconnect system
- Winching systems and deployment barge
- Testing of elastomeric mooring tethers (TTI: frequent)
- Tidal range compensation systems, possibly
- Active mooring systems for storm survival
- Fluid-filled tether systems
- Seabed attachment strategy
- Simple inelastic tension mooring system (TTI: this was for a very small scale device with specific requirements)
- Rock anchors
- Willing to divulge (TTI: but did not do so in survey)

4.5 Verbal Response Overview

The verbal responses generated an interesting set of observations. In summary it appears that the sector collectively has a good handle on the gamut of challenges and risks presented to operating, installing and mooring a WEC in typical environments and site geotechnics conditions. However, it cannot be said of course that all developers have this global and collective understanding or whether it is the collection of views which has given the broad-ranging understanding. Either way, it serves to generate a useful list of risks and challenges which WES and others can consider. Despite this apparent understanding of the techno-economic challenges of mooring a WEC many developers seemed to believe that their device requirements were not too exacting and allowed them to utilise conventional mooring systems but the cost of this does not seem to be rigorously assessed by these developers.

It can be stated that no particularly novel or unforeseen challenges or risks have been presented in this data collection exercise: all or nearly all of the challenges or development areas are being worked on currently by “somebody”.

The challenges reported by the sector cover almost all technical areas of a mooring and foundation system and of course the cost of both which is often cited. Technical challenges in the mooring system include the dynamic loading including snatch loading and long-term resistance (in relation to fatigue, corrosion, galvanic action, wear and so on). The anchoring challenge, including installation, is clearly an exacting one and it is acknowledged that a system might be designed around unspecific generic geotechnical details but highly-detailed site descriptions are required prior to installation to provide the best chance of minimising conservatism. It seems there is a desire for 'better' generic geotechnical data for design purposes but this is difficult as the 'best' geotechnical data is always specific.

There appears to be a mixed view on the mooring and anchoring supply chain. The supply chain is regarded as covering the scope from design-houses and certification bodies through component and sub-system supply to installation contractors and offshore engineering contractors. There is some distrust apparent and issues with lead times and sourcing cited frequently (and cost of course!). On the other hand some developers appear to have significant trust in the supply-chain they rely on and appear happy with performance. The provided list of suppliers of hardware and engineering is typical for the moorings and foundations industry and taps into common suppliers to the oil and gas industry and general marine industries. There appears to be a particular desire to work with certification bodies but not at oil and gas levels of conservatism which may well be a fruitful development area. Gaps in design-house knowledge were proposed. Many developers thought that "the knowledge and experience is out there" but equally many thought that gaps existed although on review of these gaps it is suggested that suppliers do exist who could fill in these perceived gaps. As with all development programmes it is all about engaging with the most ideal partners and finding them in the first place.

4.6 CONCLUSIONS

The VOC survey was sent to 99 offshore renewable energy developers, 31 responded of which 75% were WEC developers. Many of these developers have real-world development experience and are at moderate TRLs so their responses are pertinent to the sector. Furthermore their real-world experiences are likely to have influenced their responses therefore the study has captured some very interesting trends and data.

The range of devices for which responses were submitted is broad as is the range of site conditions, including geotechnics and environment, which is representative of the sector. Intended mooring systems are also broad-ranging and it is clear that the sector appreciates that there is no "one-size-fits-all" type solution: the mooring system design is intrinsically coupled to the WEC design development and the environmental conditions at the deployment site. Some developers appreciate that this requires engaging with the specialist supply-chain at early stages in the WEC design process, but not all.

The cost of purchasing, installing and operating the mooring system (including anchorage) was repeatedly cited as a key issue. The data collected generally shows that WEC developers are generally open to innovative or novel solutions if they can be qualified with high-confidence and achieve cost reductions. They identified quick-connect systems as being a key area of development along with compliant mooring systems and low-cost novel anchoring strategies. Several challenges were identified including: the dynamic nature of the system, electrical umbilical off-take, running mooring lines over sheaves, vertical loads at anchors in 'hard' seabeds, active/passive weather-vaning and active/passive storm survival strategies. Some of these challenges may be largely bespoke to the WEC sector. All of these areas could be deemed worthy of research and development (R&D) projects.

The verbal responses to the questions generated a useful compendium of risks and challenges faced by the sector relating to moorings and foundations and this could almost be used as a design 'checklist' for developers and design-houses although it is largely unsurprising when compared to existing design codes for the offshore industry. These verbal responses reinforce the above comments about key R&D areas for the sector

The mooring system classes categorised in the general state-of-the-art were also reflected in the VOC survey. A popular choice of mooring identified by the VOC survey were spread mooring systems whether catenary or synthetic semi-taut and it was decided to take these moorings classes forward to the Mooring & Foundation Case Studies.

5 MOORING & FOUNDATION INNOVATIONS

5.1 BACKGROUND

A key aspect of the Landscaping Study was to identify opportunities for step-change cost reductions as a result of innovation and improvements in associated infrastructure for WECs. It was the strong desire and intent of TTI to rigorously examine future opportunities for novel approaches and as such it was desired to conduct this in a more formalised frame-work than 'just brainstorming'. It was recognised that the collective experience of the project team leads to a degree of 'inertia' as the team members have utilised various approaches to solve mooring system challenges in the past and it can then become difficult to disengage from these approaches to allow truly novel problem solving. As such it was decided to adopt a TRIZ based approach and engage in expert facilitators to guide the project team through this in as efficient and effective manner as possible.

Section 5.2 introduces the TRIZ problem solving approach and how it was used in this project although does not intend to be a thorough description of the TRIZ process as better resources are readily available for this. Instead it shall briefly describe what was carried out during the TRIZ workshop. Thereafter some of the key avenues for innovation and research and development identified are summarised and the report concludes with an initial ranking of these avenues. The overall objective of this work package was to generate a 'menu' of choices or R&D pathways which could form the basis for a future WES call for projects.

5.2 INTRODUCTION TO TRIZ

TRIZ was adopted for this work package to provide a structured frame-work to innovation and problem solving. TRIZ is a Russian acronym which roughly translates to the "Theory of Inventive Problem Solving". Although named a 'theory' it is really a toolkit of techniques for problem solving. It is rigorous and effective and on this basis alone can be considered to be my more effective than 'brainstorming'. The TRIZ approach is utilised by many of the largest and most technically cutting-edge engineering companies in the world to promote innovation and problem solving and ultimately improve their product and offering and thus gain competitive advantage. TRIZ utilises simple general lists of how to solve 'any problem'; these TRIZ solution triggers are distilled from analysing all known engineering success, based on patent database analysis. There are also tools for problem understanding, for system analysis and for understanding what we want.

The TRIZ toolkit includes:

- Thinking in Time and Scale
- Eight Trends of Technical Evolution
- Uncovering and Solving Contradictions
- 40 Inventive Principles
- Standard Solutions for Problem Solving
- Understanding Requirements – Ideal Outcome

Aspects of these were used in this process. The TRIZ process itself was quite highly ‘trimmed’ in attempt to give the most efficient and effective path towards generating numerous innovative solutions.

Oxford Creativity (OC) were sub-contracted to facilitate the TRIZ workshop. As the TRIZ toolkit is so extensive it was deemed important and efficient to have expert guidance so the system experts could be freed-up to think about solving the problem as opposed to following a process.

The most important aspect of problem solving is of course understanding and defining the problem and this was the first step in this process. This was carried out prior to the actual workshop in concord with OC such that they could understand the problem and objectives and best prepare the workshop.

The workshop was a day event and involved twelve participants from OC, TTI, UoE and WES. It was deemed important to include WES personnel as they are a key stakeholder and the landscaping study client who possess relevant experience and knowledge in the WEC sector and M&F field.

5.2.1 DEFINING THE PROBLEM

The high-level problem statement was defined in the WES Guidance Document and Criteria Response Form. The fundamental objective was:

“identify and analyse opportunities for step-change cost reductions from innovation and improvement in the supporting infrastructure associated with the Electrical Connection and Moorings & Foundations of wave energy converter technologies”

So the generic problem can be defined as “mooring and foundation systems are too expensive”. In order to garner more insight and provide structure for the problem-solving process the project team collated a non-exhaustive list of the specific challenges in mooring a WEC which contribute to the current cost-basis for a mooring and foundation system. Briefly, these challenges included:

- Typically, shallow to intermediate water depths
  - Mean elliptical water particle orbits leading to large surge motions
  - Wave breaking and impact forces
- Very large survival sea states
- Tidal range and current velocity
  - Current often not aligned with predominant wave directions
- Fatigue and long term reliability
  - Corrosion
  - Galvanic action
  - Wear
- Wave directionality
- Vertical loads at anchor

- Availability of stable sediment at sufficient depth for cost effective anchoring
- Limited weather windows for deployment and intervention
- Wide range of device types
    - Floating
    - Sub-surface
- Wide range of mooring layouts
    - Spread moorings
    - Taut or single-leg tension moorings
- Wide range of device scales from less than 100 tonnes to thousands of tonnes
- Many operating modes and device Degrees of Freedom
- Active control of device operations mode between operating and survival
- Vessel availability and capability (and cost) for anchor install and mooring hook-up
- Compliance with oil and gas sector design codes and standards
- Condition monitoring
- Modelling non-linear system response for design

Whilst considering the challenges it has been assumed that, for the purpose of the TRIZ exercise, minimising the impact of the challenges will reduce the mooring system cost. Of course, some of these challenges may only have a weak effect on system cost but many do have a strong effect so are a suitable means of reducing system cost. In the ideas ranking section it is attempted to score the innovations in terms of their likely or predicted effectiveness in reducing system costs and therefore pass judgement on their overall attractiveness for further R&D efforts.

The project team have also conducted a Voice of the Customer survey and the outcomes broadly agreed with this list of mooring and foundation challenges although this was retrospective to the TRIZ workshop. But it is reassuring at least to know that the project team perception of the challenges was affirmed by the WEC developers and thus the TRIZ workshop focused on the correct areas.

It was noted that the generic technical problem of moorings and foundations has been solved numerous times previously for oil and gas and general offshore moorings but the distinction here is that the technical solution needs to be more cost effective and work in a different environment to most oil and gas installation Desired Outcome[23].

TRIZ often frames the problem-solving exercise by expressing the ideal outcome or solution. In this context the ideal outcome was defined as being a 'menu' of possible innovation pathways which may lead to lower cost of M&F and WEC systems.

[23] Desired Outcome is a TRIZ term…

Ranking of these pathways (technical viability, cost impact, risk, R&D effort, applicability and so on) including some reasoned thinking on potential for cost impact was additionally defined. It was desired that the menu has some genuinely innovative paths including many without existing key areas of expertise and experience.

5.2.2 Information Gathering

Prior to the TRIZ workshop TTI provided OC with pertinent information to aid their facilitation of the workshop and furnish them with sufficient background knowledge of the field. This covered:

- Problem definition
- Cause of problem
- Problem owner and stakeholders
- Background information and challenges – why the problem exists
- Prior art
- Ideal outcome definition
- Measurement of success
- Project timescales
- Desired deliverables
- Solution-space constraints

5.2.3 Workshop Agenda

The workshop covered:

- Team introductions
- Introduction to TRIZ
- Project overview including problem definition
- Initial (pre-existing) idea collection
- Ideal outcome definition
- Space and time tool (nine boxes)
- Contradictions tool and Inventive Principles
- Trends of Technical Evolution tool
- Initial ranking of collected solutions according to Ideality and Costs & Harms

Each of the tools were utilised by sub-groups of 3 or 4 people and the different groups examined differing aspects of ‘the problem’ whilst using the various tools. In this manner the landscape was thoroughly investigated in the short duration of the workshop. Through each of the idea generation tools (space and time etc) the proposed solutions were collected on post-it notes and collected in the

'Solution Park'. This allowed the ideas to be easily organised into roughly ranked groups at the end of the session allowing an initial down-select of ideas and solutions to be carried out.

Again, although the titles of the tools used listed above may not be familiar it is not the purpose of this report to describe in detail the tools used[24]. The outcomes of using the tools is much more pertinent to the landscaping study.

5.3 Outcomes of the TRIZ Workshop

5.3.1 General

Around two-hundred ideas were generated or recorded throughout the TRIZ session although there was quite a lot of repetition of ideas or themes. Without question many of the ideas were 'off-the-wall' but the importance of these should not be discounted as they often acted as 'triggers' for other team member's idea generation which, at times, brought the concept or the morsel of an idea closer to a realistic or practical solution. Of course, in such a rapid idea-generation session the assessment of practicality can only be limited and at times expert advice would need to be garnered to be able to conclude on the viability or otherwise of an idea. The further benefit of idiosyncratic idea generation is that is it a strong indicator that the team members did indeed break-out of psychological inertia whereby pre-existing methods, techniques and tools are preferred and this was an important objective of the TRIZ workshop.

5.3.2 Idea Rough-Cut Ranking

As described above the two-hundred ideas were quickly and roughly ranked at the conclusion of the session. The ideas were split/grouped into four areas:

1. High benefit and low cost/harm
2. High benefit and high cost/harm
3. Low benefit and low cost/harm
4. Low benefit and high cost/harm

Where clearly Group 1 are the most obviously attractive and Group 4 the least. Group 4 are not really expected to be viable and are rejected at this stage although morsels of these ideas may still prove fruitful in the future due to technological or materials developments. Group 3 ideas are also not fantastically attractive and would require significant development effort to promote them to higher rank. As such, they are also rejected herein as there are a significant quantity of ideas in the two best groups to focus early R&D efforts on. Many of the rejected ideas were in the 'off-the-wall' camp and the more attractive ideas are more classically conventional or based on this. Many ideas were recorded which were not particularly innovative as such but are recorded herein for completeness.

[24] There are numerous TRIZ resources available online for example:

5.3.3 Solution Types

Within the Group 1 and Group 2 solution ideas there was a clear grouping of idea type or area of focus. Across the two groups the type of solutions proposed covered:

- No mooring system
- Monitoring and control
- Mooring line
- Novel materials and material applications
- Infrastructure sharing / Combining functions
- Anchor
- Marine operations
- WEC system level (meaning full system changes to minimise mooring costs)
- Biomimicry

Each of the solution types listed above appeared in both Group 1 and Group 2.

Idea Generation

The following sub-sections give an overview of the ideas generated within each solution type listed above. It is attempted to provide a high-level SWOT analysis for each type or solution.

No Mooring System

The generic concept of removing the mooring system entirely appeared on numerous occasions. Potential solutions included those with and without station keeping. Station keeping was envisaged by the use of thrusters to impart the required forces. Without station keeping a free-floating device with on-board energy storage was envisaged which is periodically recovered to 'collect' the stored energy which could be in the form of electrical in batteries or chemical in e.g. hydrogen or otherwise. It was anticipated that some directional control would be required for this concept.

Monitoring and Control

The arena of monitoring and active control is broad. One aspect deemed beneficial was improvements to remote monitoring of mooring systems including load monitoring. From experience, this is typically challenging and unreliable for mooring systems. As a result, mooring system design is often over-conservative and minimising conservatism though more intelligent and effective monitoring may yield cost-improvement paths.

One specific idea that arose, which we know is currently in development, is the use of load-measuring devices integral to the rope structure and therefore do not require numerous additional connectors and hardware. Additional hardware and connections are generally to be minimised to reduce costs and minimise failure points.

Other rope-integral monitoring devices or techniques could be envisaged to, for example, indicate internal condition or rope wear, indicate external rope wear, or assimilate fatigue data for lifetime projections. An example of an analogous systems is the real-time fatigue assessment software used in coiled tubing well interventions in the O&G industry. This could be transferred to a Cyclical-Bending-

Over-Sheave (CBOS) application in a WEC whereby an encoder and load pin at the sheave assembly could be used, with appropriate bench-marking and algorithms, to continuously monitor the system's residual strength or estimate time-to-failure. If integral rope load monitoring can be developed a similar algorithm could be developed to predict rope residual strength and time-to-failure. The benefit to understanding time-to-failure is of course to maximise the use of a given component (thus maximising return on investment) and/or avoiding unplanned failures and the associated repair costs and device downtime which can have a strongly negative effect on LCOE.

Discussion on the use of active control solutions predominantly focused on the mooring line and its properties. It was envisaged that active control of length, axial stiffness and axial damping could all be useful avenues. When considering control it may be on a wave-by-wave (or within wave) frequency or on much longer period such as seastate-to-seastate, day-to-day or season-to-season. An example of long-period tuning (e.g. seastate-to-seastate) would be to alter the properties of the mooring system to promote load-shedding in survival sea states. A list of sub-systems of components which could provide this functionality includes:

- Winching
- Constant tension type winches with control such that the load-elongation properties can be tuned as desired
- Linear actuators – either hydraulic or pneumatic – for length, stiffness and damping control
- Fluid-filled members with tunable load-elongation properties (due to e.g. internal pressure variation)

Mooring Line

The mooring line is obviously a key component or sub-system of the mooring system and is therefore the focus of interest for cost-reductions and functionality enhancements. The moorings industry has actually seen steady development and innovation in this area for quite some decades. Much of this improvement is related to materials development as the latter half of the 20th century was fruitful in the development of numerous different polymers with differing properties that have proven useful in different applications. There has been significant R&D efforts to apply and qualify these materials and development in specific rope structures and coatings to promote long life for the different polymers. A key example of this is the recent qualification of parallel strand construction nylon ropes (see Case Study in Section 3.3.3) which offer high elongation properties (compared to polyester, HMPE, steel etc.) coupled with excellent fatigue lives. This has proven to be an enabling development for many marine renewables applications. The development and qualification of large polyester ropes was enabling for the deep water O&G market thus showing the commercial value of some of these recent developments. Development for steel lines is understandably slower due to the maturity of the industry but progress has been made recently in the application of higher grade steels in mooring chains which provide greater minimum break loads (MBL) for lower mass which can be beneficial in some applications. Corrosion and wear remains an issue.

As the development of new polymers is a highly specialised area conducted by few global brands it is difficult for the project team to envisage and predict where these material developments will or can lead. What can be said however is that the development of new polymer materials for fibres has continued into the latter parts of the 20th century and beyond with developments of e.g. Kevlar and aramids so it is not unreasonable to envisage further progress in this arena. One novel development path which has been the interest of polymer scientists for quite some time is the production of synthetic spider silk with astounding specific strength and elongation properties.

In addition to innovations in the actual materials of the lines some more 'global' innovations were generated.

So within that context the ideas generated for mooring line innovations included:

- Utilise short-life but cheap and easily replaceable lines
- Utilise different line materials and properties in series different portions of the line assembly requiring different functions (quite common e.g. chain for bottom contacting, polyester for light-weight in water column but novel variations on this theme to achieve specific combinations of function)
- Utilise elastomers in mooring line for increased compliance
- Utilise different materials in parallel to develop non-linear stiffness characteristics such as end-stops to elastic portions, increasing or decreasing stiffness with elongation, adding redundancy or load-bypass in case of main-line failure
- Utilising highly definable and steady-state line properties to impart load-limiting fuse-type function
- Changing fibre rope line structure from round cross-section to flat (e.g. woven belt) which can optimise CBOS applications or minimise contact pressures in fairlead applications
- Development and application of very high strength steel chains to minimise mass to strength ratio

Novel Materials and Materials Applications

The application of novel materials relating to the mooring line has been discussed above. More generally the use of novel materials was considered for other parts of the system. For ideas which were grouped into this section the idea was typically generic "use novel material" as opposed to a specific application of certain novel material. The novel materials typically included as-yet unfound polymers and carbon fibre. Synthetic spider silk was discussed but as mentioned above this is still very early in development phases.

A composite mooring line connector is under development currently with a basalt fibre reinforced aluminium load bearing core and external covering of low-friction polymers to promote long rope life. This is a good example of innovative application of materials. Fibre reinforced aluminium metal matrices are well known in other industries and basalt fibre reinforcement is akin to this.

Infrastructure Sharing / Combining Functions

Infrastructure sharing was specifically noted as a possible R&D avenue in the WES call guidance document and concepts for this did appear numerous times throughout the TRIZ session. Examples of this included:

- Sharing of anchors for multiple lines and or devices
- Mooring line incorporates electrical off-take functionality

    - This may be in the form of single ‘line’ with strength and conductor cores
    - Or parallel line with piggy-back clamps to carry umbilical on structural line
- WECs incorporated into systems or structures which provide additional functionality such as combined floating wind and wave, fixed wind installations, aquaculture installations, breakwaters, reefs and suchlike.
- Mooring an array of WECs in a ‘surface-grid’ of mooring lines arranged within a number of anchors fewer than the number of WECs. It is noted that some device developers are working on concepts like this. There may be advantages in total mooring system load at the anchor due to the phase shifts in loading between WECs which become self-reacting within the grid as opposed to being wholly reacted at the sea bed. It is further noted that this is an essence of TRIZ inventive principle “Periodic Action” or “Rhythms co-ordination” within the Trends of Evolution.

Anchor

The anchor was a fruitful area of idea generation. This is likely due to the challenging nature of anchoring for WECs coupled with the broad range of device types (and thus anchor load vectors) and the highly variable nature of the sea beds for WEC sites. As there is no single solution to satisfy these requirements then numerous solution types are required.

A key area of focus of idea generation was in the arena of gravity base anchors (GBA). These are often technically appealing owing to their simplicity and suitability for a wide range of sea bed conditions. However, the cost of material and especially material emplacement can be severe due to the masses required for high-force GBAs. This then opens up the field of marine operations and design for deployment as solution areas.

A key TRIZ Trend utilised here was “Segmentation” but this is hardly revolutionary. Many existing gravity anchors are either assembled at site from modular blocks of concrete or steel or are hollow caissons which are then flooded or filled with some material. One somewhat novel approach generated, which we are not aware of being carried out to date, was utilising an open-topped concrete caisson which is floated out to site and flooded to place on seabed. This however does not generate significant anchoring force due to relatively low submerged weight. The novel aspect was then utilising a rock-dumping vessel to (presumably) relatively cheaply transport aggregate, rocks or otherwise from shore to the site and dumping the material into the anchor void to significantly increase the holding capacity of the anchor.

Other ideas included:

- Change form of gravity anchor from ‘boxy’ to ‘rounded’ to minimise hydrodynamic self-loading and/or generate flow induced down-thrust (in tidal sites)
- Change anchor material density (not uncommon by e.g. adding steel to concrete GBAs). The GBAs in the EMEC SCAPA wave test site utilised this approach to achieve block density in the order of 4 Te/m^3 which is considerably higher than standard concrete.

- Increase sea bed contact friction through surface preparation
- Increase sea bed horizontal holding capacity by imparting large-scale roughness (provide shear-keys). This is a fairly typical solution and may be referred to a ‘skirt’ for GBAs in soft seabed conditions.
- Utilise ‘alternative’ energy source to deploy embedment anchors. A currently developing area of this is free-fall ‘torpedo’ anchors (otherwise known as Deep Penetration Anchor – DPA - Figure 66) that use free descent through the water column to embed an anchor into soft soils. The anchoring characteristic may be thought of as somewhere between a driven pile and drag embedment. The installation technique means that large bollard pull AHVs or pile hammers are not required to install conventional embedment anchors and in principle more control may be achieved over the positioning of the anchor. This type does have approval in principle from DNV and has been tested at full-scale in O&G deployments. A further subset of this technique is propellant driven anchors, very much resembling a real torpedo. It is thought that the US Navy experimented with such a system some decades ago but there is minimal evidence found of actual use or further development and the hazards of such a device are plain to see. What’s more, it is unclear whether they would be any more effective than more standard solutions in harder soils.
- Hybridised gravity anchor solution whereby weight provides majority or all of vertical load resistance but piling through the GBA provides horizontal load resistance. A development of this would be where the GBA forms a subsea drilling template for the piles. The piles may be small and numerous or larger and fewer. Drilling on the seabed could be significantly more viable and cost effective than surface based drilling. This leads us onto the second main type of anchors discussed in the TRIZ session; piled anchors.

Figure 66: Deep penetration (torpedo) anchors for cohesive sediment sites (source: Deep Sea Anchors).

Piled anchors are used extensively in the marine and offshore market. There are two main types of piled anchor; driven (hammered or screwed) and drilled. Driven piles are suitable for use in 'soft' seabed soils and drilled in hard seabeds. Drilled piles are often grouted following installation. Many oil and gas installations and fixed offshore wind turbines have accesses to good sediment depths and driven piles are used extensively here. This is seen as being a less viable approach for WECs (and TECs) as the availability of sufficient depth of sediment is less likely to occur in energetic shallow or intermediate water depth sites. As such drilled piles are technically more viable, in general, but come with exacting installation requirements and costs. Beyond shallow water exceedingly expensive O&G vessels are required. In shallow water jack-up barges normally used in nearshore civil engineering activities make the cost somewhat more tenable but remain expensive. To address this issue numerous organisations have worked or are working on subsea drill rigs to install drilled piles. As such, although the concept of piled anchors appeared numerous times throughout the TRIZ session few of the ideas were truly innovative. That being said, it is envisaged that there is broad scope within this arena for further development and cost optimisation. As mentioned above combining functions from different anchor types may prove attractive. Further, subsea operations with surface control and power supply appears fruitful. Companies actively or recently working on subsea piling include AWS Ocean Energy with Self-Drilling-Pile-Solution concept, Bauer Renewables (Figure 67), Sustainable Marine Energy with their Raptor Rock Anchor and Intecsea (a WorleyParsons Group company) working on marine micropiles (although information is not recent on this).

The development of subsea drilling rigs such as the SME Raptor and Bauer have taken onshore practices and machines and adapted them for subsea use. This solution appeared during the TRIZ session with the generic concept of marinising and adapting onshore construction equipment (e.g. excavators, bulldozers, piling rigs) or adapting their principle and making bespoke machines to carryout offshore construction activities which could lead to cost reductions in gravity anchor or piled anchor installation and build. IHC Merewede (Royal IHC) are leading proponents of this approach and Figure 68 shows one of their seabed trenchers.

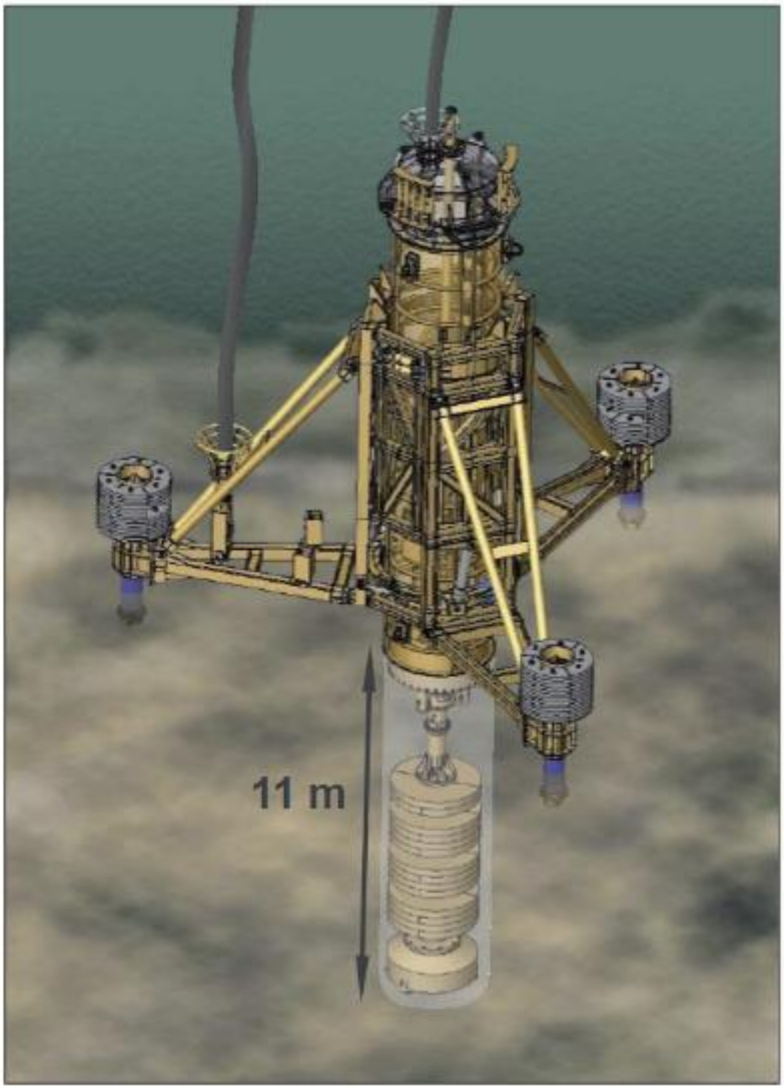


Figure 67: Bauer Renewables subsea drill rig (source: Bauer Renewables).

Figure 68: Royal IHC subsea trencher[25]

Minor improvement paths were generated for drag embedment anchors and this is likely due to their highly-developed status and attractive cost base already. One modification proposed was to have the fluke area in multiple sections so could be 'folded up' for transport and additional sections added to increase the fluke area for specific anchor locations. Further, the Vryhof Stevshark type anchors are designed to operate in shallow sediments with hard rock underneath and can load bear on the fluke tips as opposed to over the whole fluke area. Developing this a little further resulted in ideas similar to camming or expanding or grappling hook type rock climbing hardware which could develop anchors to very rough rocky seabeds.

The essence of drag anchors attractiveness is the fact that they use something which is already there (sediment) to achieve their function and are therefore cost effective; we do not need to transport in thousands of tonnes of material. This 'TRIZy' principle was applied to other anchor types and the question asked, "why not use existing rock to achieve something similar?" In principle piled anchors in rock somewhat address this path but are operationally unattractive. An idea was developed to propose using subsea trenching to cut a rock 'bollard' around which a mooring line (chain, wire rope or abrasion protected fibre rope) can be looped. This would look somewhat like a winter mountaineering rope snow anchor as shown in Figure 69. In this way it was envisaged that a drag type anchor restraint could be achieved in rocky seabeds without needing to build an expensive GBA. It may also be possible to drill downwards so the loop is in the vertical plane. As with all anchors robust geotechnical surveys would be required.

[25] https://www.royalihc.com/en/products/offshore/subsea-equipment/canyon-helixs-itrencher

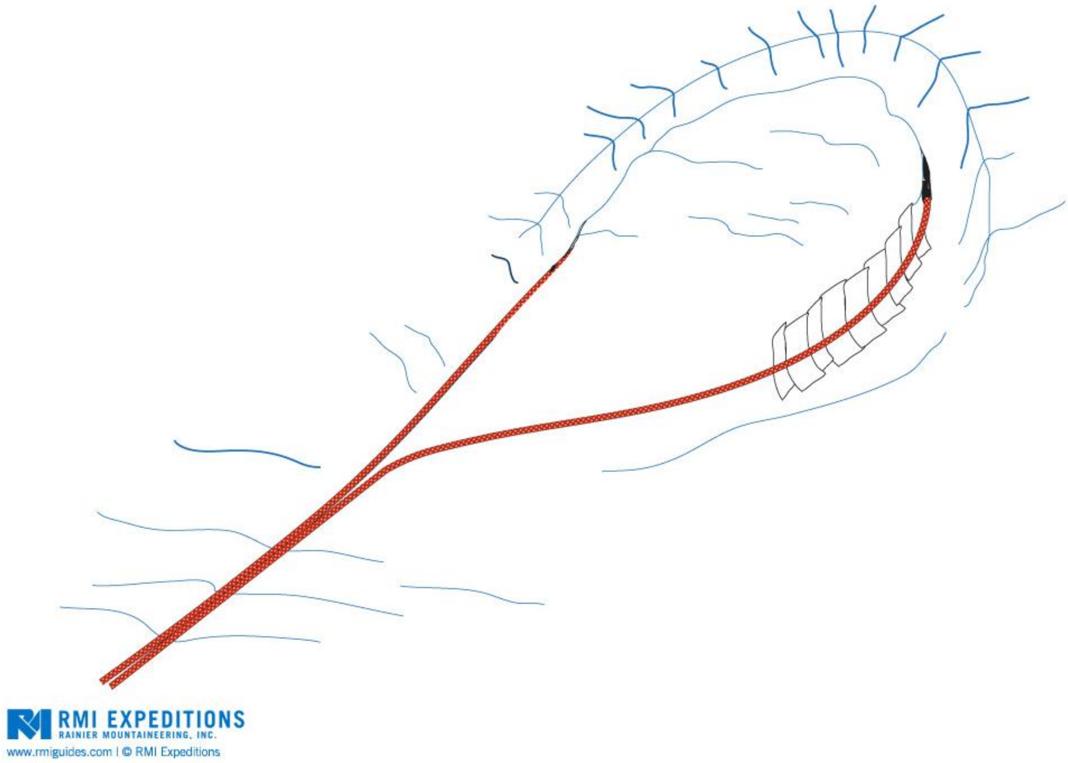


Figure 69: Snow anchor 'lasso'[26]

[26] https://www.rmiguides.com/technical/expedition-climbing-skills

A further development of drag or vertically drag anchors was suggested on numerous occasions throughout the session and this was something like a 'sand drogue' that functions in a similar way to a greatly scaled up version of a tent anchor. It was also offered that by integrating this system with a frond mat then fronds could promote sediment deposition thus increasing anchor capacity with time or at very least mitigating the effects of scour.

The use of geotextile materials to contain ballast for gravity anchors is not wholly novel as an MRCF project developed a modular gravity bag anchor where the ballast was wholly contained and the weight from numerous sub-bags agglomerated in a fibre rope net.

Marine Operations

Marine operations was discussed throughout the session and was pertinent to many of the proposed innovations. All of these have been discussed already in the context of anchoring solutions such as marinising onshore civil construction equipment, using low-cost vessels to construct modular GBAs, tow-out and ballast and rock dumping to build GBAs.

WEC System Level

A number of innovation paths were suggested in the TRIZ workshop that aimed at reducing the mooring and anchoring challenges by adapting the overall system architecture and design at the WEC or WEC farm level. One such idea has already been noted which is the 'mooring grid' whereby an array of devices become internally-reacting self-reacting as opposed to wholly ground reacting and some developers are known to be working on such an architecture.

The prospect for floating out the device with foundations and/or anchors attached and then the entire system self-installing was also deemed attractive and this is similar to the route taken by Laminaria. With the correct soil conditions (sediment) it may even be possible for free-fall (torpedo) anchors to be floated out with the device and installed simultaneously.

Installing the PTO in series with the mooring line or lines is in development with various device developers and was deemed worthy of further R&D.

Biomimicry

Biomimicry is the design and production of materials, structures and systems modelled on elements of nature to solve complex problems. Various ideas in this arena arose throughout the TRIZ workshop. One key one examined the concept of kelps and seaweeds which have numerous attractive properties such as:

- Compliant structures such that they can move with the waves and survive energetic sea conditions

- Different root-like anchoring elements for muddy, sandy or rocky seabeds. The muddy root-like structure utilises and complex 'tangle' of growths to achieve holding. The sandy anchor can have elastic bulb-like structures which can contract and pull the structure into the substrate as a survival mode. The rock anchor has a flattened base which adheres to the surface (Figure 70).

- The seaweed fronds can often act as retarders to the bottom water particle velocity which may allow suspended sediments to drop out of suspension and therefore accumulate around the fronds.

It is clear to see why kelp alone provides much inspiration for a biomimetic approach to anchor and survival mode design. Each of the anchoring techniques for the kelp are worth further consideration. The prospect of utilising artificial fronds to attract sediment is also seen as attractive. Some pipe and cable protection methods utilise such a technique already such as the frond mats shown in Figure 71.

Alternative biomimetic approaches which may be fruitful include:

- Use of cephalopod type suction pads to achieve holding on smooth, hard surfaces.

- The ‘system level’ above cephalopod suction pads, the limb or tentacle, is known as a muscular hydrostat. This is a controllable structure with no skeletal support, actuated by water pressure within the muscle structure. In some respects novel mooring tethers based on hose-pump type principles could be regarded as a subset of this kind of ‘technology’ and other avenues may prove fruitful. In the simplest terms we could consider an actuator (for e.g. moving a pin in a quick connect system) which comprises a simple flexible bladder with no moving mechanical parts or seals required (like a conventional hydraulic linear actuator).

- In principle many biological systems utilise massive quantities of tiny features to achieve a function (such as octopus suckers over a large area to achieve holding power) and apply this TRIZy technique to the mooring and anchoring challenges may be fruitful. In other words instead of thinking of one massive anchor which is hard to install think of the system at a near-micro level and how the same overall function could be provided by numerous tiny components or sub-systems.

Figure 70: Kelp holdfast anchor (source: Heiko Hübscher - Own work, CC BY-SA 2[27])

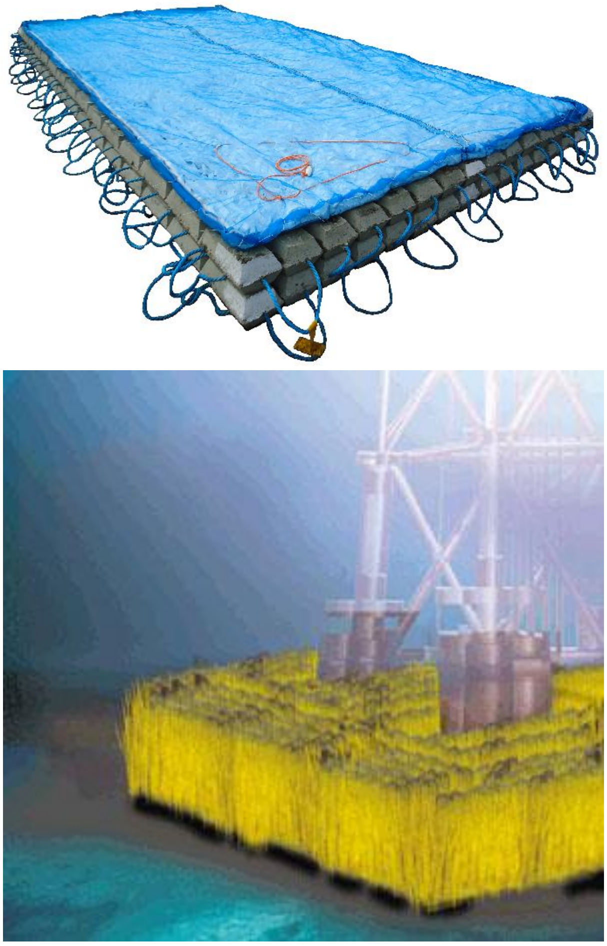


Figure 71: Frond mats for scour protection (source: Subsea Protection Systems)

5.4 Idea Ranking

As mentioned, a degree of ranking occurred on the day of the TRIZ workshop and the ideas reported herein come from the two most promising camps: low cost and high benefit and high cost and high benefit (where cost is any harmful effect). Thereafter, each workshop attendee was given three votes for their most promising idea at the end of the day. This generated a fairly wide spread of favoured concepts with only a couple of concepts attracting more than one vote. These ideas are therefore considered as being immediately attractive for further investigation and they were:

- Snow anchor type 'lasso' anchor
- Autonomous load monitoring
- Umbilical protecting quick-release method (in extreme survival mode)
- Improved understanding and definition of governing physics in design and simulation

[27] https://commons.wikimedia.org/w/index.php?curid=1163782

The remainder of this section of the report shall collate the full list of discrete ideas and perform a first-pass Pugh-type matrix analysis to attempt to generate a ranking for most attractive ideas. The list of ideas uses a 'short-form' description which relates to the descriptions of the ideas given above.

It is noted that the ranking in the Pugh matrix can only be a high-level assessment at this point in time, based on experience, knowledge and engineering judgement. Given the preliminary nature of the ideas and ranking the scores used are 1 to 3 for comparisons. Higher scores are 'good'. It is also noted that in the case where, for example, a certain anchor type is suited to one soil condition it is scored for that condition only as it is recognised that many solutions are specific as opposed to generic.

For the Pugh analysis the simple set of three criteria are used for ranking and even are given equal importance so no weighting score is used:

- Practicality: the judged probability of the solution becoming a realistic solution
- R&D effort: the judgement on the amount of development work required to take the idea to market at high TRL
- Cost impact: the judgement on the potential beneficial impact on LCOE

Table 12 shows the Pugh matrix including total scores. The ideas are ranked according to their total score which gives an indication towards their attractiveness to develop further. As noted above many ideas are not fundamentally radical or wholly innovative and it is interesting to note that some of the ideas with best scores are very practical solutions or evolutions of existing technologies and techniques. Given that practicality is one of the judgement criteria this is perhaps unsurprising. It also means, therefore, that ideas with a lower total score should not be discounted from R&D effort as some step-changes in approach or technology could take a concept from low practicality to high and therefore provide an effective overall solution to some of the challenges.

Table 12: Concept idea ranking in evenly weighted Pugh matrix

Idea	Practicality	R&D effort	Cost impact	Score
Rock dumped GBA	3	3	3	9
Mooring line active control (length)	3	3	2	8
Readily interchangeable mooring lines	3	3	2	8
Use numerous materials in series	3	3	2	8
Use numerous materials in parallel	3	3	2	8
Mooring grid for multiple WECs	3	2	3	8
GBA density increase	3	3	2	8
GBA shear keys	3	3	2	8
Free-fall embedment anchors	3	2	3	8
Hybrid GBA-pinned anchor	3	3	2	8
Anchor bags	3	3	2	8
Frond matts for sediment deposition	3	3	2	8
Biomimicry - drag reduction	3	3	2	8
Load monitoring	3	3	1	7
Utilise elastomers in mooring line	3	2	2	7
Use flat ropes	3	2	2	7
Anchor sharing	2	2	3	7
Hydrodynamic optimised GBA	3	2	2	7
Subsea drill rigs for anchoring	2	2	3	7
Lasso anchor in hard seabed	2	2	3	7
Mooring line condition monitoring	3	2	1	6
Mooring line active control (stiffness)	2	2	2	6
Load-limiting fuse function in line	2	2	2	6
Use of composites for line connectors	2	2	2	6
Combined mooring and umbilical line (piggy back)	2	2	2	6
Seabed friction enhancement	2	2	2	6
Folding drag embedment anchor	2	2	2	6
Grappling hook anchor for rocky seabeds	2	2	2	6
Sediment drogue anchor	2	2	2	6
Biomimicry - hydrostatic muscle	2	2	2	6
Thruster position keeping	2	2	1	5
Develop new synthetic polymer	2	1	2	5
Infrastructure sharing (e.g. breakwaters)	2	2	1	5
Self-installing anchors off WEC platform	1	1	3	5
Biomimicry - kelp holdfast anchors	2	1	2	5
Free floating and on-board storage	2	1	1	4
Very high strength chains	2	1	1	4
Combined mooring and umbilical line (coaxial)	1	1	2	4

Idea	Practicality	R&D effort	Cost impact	Score
Propellant driven embedment anchors	1	1	2	4
Biomimicry - suction pad anchors	1	1	2	4

Following the first pass of the Pugh matrix a further analysis was performed with weightings included. Cost impact and practicality were both given equal high importance (a value of 3) and R&D effort was reduced in relative importance to a weighting of unity. This had a fairly modest effect on the outcome with the top ranked ideas changing only slightly as shown in Table 13. Of course other weighting factors, and scores, can be used to give further different results but these two matrices probably give a reasonable view on the most attractive set of ideas.

Table 13: Weighted Pugh matrix analysis

Idea	Practicality	R&D effort	Cost impact	Score
Rock dumped GBA	3	3	3	21
Mooring grid for multiple WECs	3	2	3	20
Free-fall embedment anchors	3	2	3	20
Mooring line active control (length)	3	3	2	18
Readily interchangeable mooring lines	3	3	2	18
Use numerous materials in series	3	3	2	18
Use numerous materials in parallel	3	3	2	18
GBA density increase	3	3	2	18
GBA shear keys	3	3	2	18
Hybrid GBA-pinned anchor	3	3	2	18
Anchor bags	3	3	2	18
Frond matts for sediment deposition	3	3	2	18
Biomimicry - drag reduction	3	3	2	18
Utilise elastomers in mooring line	3	2	2	17
Use flat ropes	3	2	2	17
Anchor sharing	2	2	3	17
Hydrodynamic optimised GBA	3	2	2	17
Subsea drill rigs for anchoring	2	2	3	17
Lasso anchor in hard seabed	2	2	3	17
Load monitoring	3	3	1	15
Mooring line condition monitoring	3	2	1	14
Mooring line active control (stiffness)	2	2	2	14
Load-limiting fuse function in line	2	2	2	14
Use of composites for line connectors	2	2	2	14
Combined mooring and umbilical line (piggy back)	2	2	2	14
Seabed friction enhancement	2	2	2	14
Folding drag embedment anchor	2	2	2	14
Grappling hook anchor for rocky seabeds	2	2	2	14

Idea	Practicality	R&D effort	Cost impact	Score
Sediment drogue anchor	2	2	2	14
Biomimicry - hydrostatic muscle	2	2	2	14
Develop new synthetic polymer	2	1	2	13
Self-installing anchors off WEC platform	1	1	3	13
Biomimicry - kelp holdfast anchors	2	1	2	13
Thruster position keeping	2	2	1	11
Infrastructure sharing (e.g. breakwaters)	2	2	1	11
Free floating and on-board storage	2	1	1	10
Very high strength chains	2	1	1	10
Combined mooring and umbilical line (coaxial)	1	1	2	10
Propellant driven embedment anchors	1	1	2	10
Biomimicry - suction pad anchors	1	1	2	10

5.5 Conclusions

A key aspect of the Landscaping Study was to identify opportunities for step-change cost reductions as a result of innovation and improvements in associated infrastructure for WECs. It was the strong desire and intent of the report authors to rigorously examine future opportunities for novel approaches and as such it was decided that the most appropriate way to conduct this was a more formalised approach rather than 'just brainstorming'. It was recognised that the collective experience of the project team could lead to a degree of 'inertia' as the team members have utilised various techniques to solve mooring and foundation system challenges in the past and it can then become difficult to disengage from these approaches to allow truly novel problem-solving. As such it was decided to adopt a TRIZ-based approach and bring in the expertise of facilitators to guide the project team through this in as efficient and effective manner as possible.

The TRIZ workshop was a fast-paced introduction and application of TRIZ principles to the challenging area of cost reduction in WEC mooring and foundation systems. The team who participated in the event covered a wide range of experiences and knowledge from physics graduates with minimal hands-on experience of mooring system design to decades-experienced subject matter experts in the field and numerous people with detailed wave energy converter experience. This ensured enough breadth of experience to 'break' the psychological inertia of the experienced hands and bring in fresh perspectives and knowledge from other sectors. Meanwhile, the experienced hands could frame the problem, previous concepts and solutions and think beyond the limits of the current state-of-the-art. With this mix the workshop was wide-ranging and as reported generated almost 200 ideas, although that did include some repetition.

It was mentioned at times throughout the workshop that idea generation was difficult and the use of TRIZ does not automatically yield "light-bulb moments". However, by the end of the session when all the ideas were brought together and viewed as a whole it was clear that a thorough and useful exercise had occurred. This report has attempted to summarise the process and the outcomes of the workshop. As this is the work of a small team it is hoped that this will provide inspiration to the report readers and yield further fruitful pathways of idea generation. Further, it is hoped that if the introduction to the TRIZ process is new for some readers it will provide access to a useful tool for the wave energy sector.

A summary table from the Pugh matrix ranking was developed by TTI and this demonstrated that, against the three criteria chosen, a set of the ideas which give strong potential to achieve the objectives and could be worth focused R&D effort to take them to higher TRLs for the wave energy sector.

The Pugh matrix identified and ranked 40 ideas considered worthy of further consideration. A large proportion of the ideas generated related to anchoring. The mooring and foundation case study highlighted that conventional gravity based anchors (GBAs) are unaffordable. However, the Pugh matrix identified some opportunities in the development of GBAs. If the mooring loads transferred to a GBA can be reduced (e.g. via compliance), then this will improve their attractiveness as the holding requirements will be lowered. Equally, some early array developments on rocky seabeds may not be able to amortise the costs of offshore drilling vessels, and an innovative GBA or hybrid design would be an attractive solution. Less specific ideas were generated in relation to innovate rock anchoring or drilling, although the lasso anchor is worthy of further consideration. There are clearly opportunities in the development of semi-autonomous underwater drilling units. While drag embedment anchoring is already highly evolved and very efficient in the right seabed conditions, there were a number of ideas generated using an alternative approach. In terms of reducing line and anchor loads, highly compliant (e.g. elastomeric) mooring components are of interest and ideas were generated in relation to mooring line active control and combined power capture. There were quite a few ideas generated in relation to biomimicry. Other ideas included piggybacking power export or data umbilicals with mooring lines and mooring line condition monitoring.

6 MOORING & FOUNDATION CASE STUDIES

6.1 OVERVIEW

The purpose of the scenario-based study was to show the techno-economic impact of mooring compliance on system cost and weight, including foundations. The impact was assessed for a range of WEC scales, water depths, footprints and foundation types. For the purpose of this study, the comparison was conducted between two mooring system types with compliance provided by mooring line axial compliance (e.g. nylon) and catenary geometry (e.g. chain). Both of these mooring types were of interest to participants of the VOC survey. It is recognised that these are not the only solutions for providing station keeping. Alternatives include combinations of wire, other synthetics, clump weights, buoys, shock absorbers etc. However, it was not practical to compare all these options within this study, also for newer mooring innovations it was not possible to substantiate their performance and costs or how scalable the technology is to withstand the larger loads associated with larger displacement devices considered in this study. Rather the objective of the scenario study was to demonstrate and quantify the potential impact mooring compliance could have on mooring, anchor and device loads, installation & marine operation requirements and relative cost of energy based on known-knowns (e.g. based on data and assumptions that we can substantiate). For this study only three types of anchor were considered namely: gravity base (GBA), drag embedment (DEA) and vertical uplift anchor (VLA). No consideration was given to piling or rock anchoring and it is recognised that suitability and cost can be very site specific. The study at a high-level provides a benchmark for the development of alternative innovations for mooring compliance and identifies the economic opportunity for other types of foundations.

Data from all simulation runs were then analysed and selected trends plotted. Key findings in the context of the Landscaping Study were then summarised. The following parameter trends have been investigated:

- the influence of compliance on line MBL with device scale
- the influence of footprint on line MBL with line type
- the influence of water depth on line MBL with line type
- the impact of MBL requirement on mooring line weight
- the impact of MBL requirement on the cost of mooring lines
- a comparison of device maximum excursions with total line costs and characteristic line tensions
- a comparison of foundation mass with type
- a comparison of foundation cost with type

It should be noted that for a number of the cases the simulation results indicated that spare chain was left on the seabed throughout the simulation. For this reason and to ensure a fairer comparison the chain mooring lines were trimmed back to minimum suspended length plus 10m 'spare'.

6.2 ANALYSIS APPROACH

To provide a qualitative assessment of the potential benefit of using compliant materials in MRE mooring systems the study investigated a total of 416 chain catenary and taut synthetic rope scenarios. In this context, a 'taut' mooring system is defined as one where system compliance is provided by the axial stiffness of the line materials as well as rotation of the fairlead and anchor connection points. For each scenario, the lowest cost and feasible solution (in terms of Ultimate Limit State analysis) were identified. The scenarios considered 3x device scales, 2x line setups (chain and synthetic rope), 2x line axial stiffness values (synthetic rope only), 2x grades of chain, 4x water depths and 5x anchor footprint radii in addition to (up to) 3x anchor types.

Three scales of floating cylindrical devices were chosen which all were dimensionally similar[28]. The range of device masses were 5000T, 1000T and 100T and these devices are also referenced in the report as the BC1, BC2 and BC4. The scale range was considered to be fairly representative of the sector from smaller 100T point absorbers to large devices at 5000T as reflected by the device scales reported in the VOC survey.

The process for obtaining mooring system CAPEX and mean time to failure (MTTF) for each scenario involved the use of a modified version of the DTOcean mooring and foundation module code [109] coupled to the commercial mooring system package Orcaflex [113]. The DTOcean suite of tools was developed to assist the planning of wave and tidal energy device arrays covering array layout, electrical infrastructure, mooring and foundation systems as well as operational and lifecycle aspects. Due to the overall requirements governing the processing time of the DTOcean Tool, some analysis simplifications were necessary in the mooring and foundation module, the suitability of which was assessed during the DTOcean project [111]. In the absence of processing time constraints in the WES Landscaping Study reported herein, portions of the mooring and foundation module code were adapted to include the use of dynamic systems solver Orcaflex. In this section, the inputs and assumptions used by the modelling process are outlined.

6.2.1 Assumptions and Inputs

The assessment process was automated with Quality Assurance checks carried out on the results. The input parameters for each scenario are listed in Table 14, with further details regarding the device physical parameters and a breakdown of the scenario parameters is provided in Table 27 to Table 29 in the Appendices. The main assumptions made during this analysis are as follows:

- The device is cylindrical and modelled as a Morison 6 degree-of-freedom (DoF) buoy because the maximum device diameter is small compared to the incident wavelength[29].
- One environmental condition is considered comprising a collinear irregular (survival) sea state and current. While it is acknowledged that wind loading can be important it is not considered in this study due to the complexity of modelling this in Orcaflex on 6 DoF buoys.
- The coupled system responses demonstrated by the three device scales may not be resonant, and hence the simulated mooring tensions reported herein may not represent the highest possible mooring loads.
- In order to keep the outcomes of the study generic, a PTO system is not included in the analysis. It should therefore be noted that the influence of mooring type and geometry on the level of power generation was not considered in this analysis.

[28] Whilst it is acknowledged that not all WECs are cylindrical, this generic shape is often used for point absorber studies.

[29] An Airy wave with a period equal to the peak period of 18s studied here would have a wavelength equal to 420.7m. It is acknowledged that in an irregular sea-state the device will be subjected forces influenced by a range of wavelengths.

- The mass and volume of the device are set such that it is buoyant and floats in still water at a draft which is equal to half the cylinder height and has a centre of gravity at the keel.
- A constant axial stiffness is used for chain (based on the bar diameter). Two axial stiffness ratios are used for synthetic ropes: EA/BL = 4 and 8 (where EA is the rope axial stiffness and BL is the break load of the component). The EA/BL factor of 8 is based on a linear approximation for storm stiffness of parallel-strand nylon rope. The EA/BL = 4 is for a softer equivalent rope for comparison purposes, see note below. Further commentary on representing synthetic ropes in mooring system analyses can be found in Section 3.10.2.
- Two grades of chain strength are considered: Grades 3 and 4. Other grades of chain (see Section 3.9.2) may facilitate other mooring system designs although the grades used are quite representative of those often used by MRE developers.
- For each scenario, the number and length of lines and components used are equal. A 60-degree separation angle is used between each pair of seaward and leeward lines (Figure 72). The mooring system is orientated to the incoming wave and current direction to enable load sharing between the pairs of seaward and leeward lines. The anchor positions are located on a pitch circle diameter governed by the specified footprint radius.
- Pretension values of 20% and 5% MBL are used for the synthetic rope and chain scenarios respectively.
- The seafloor is assumed to be level and homogenous medium sand. It is also assumed that sufficient sediment depth is present for all of the anchor types considered in this study.

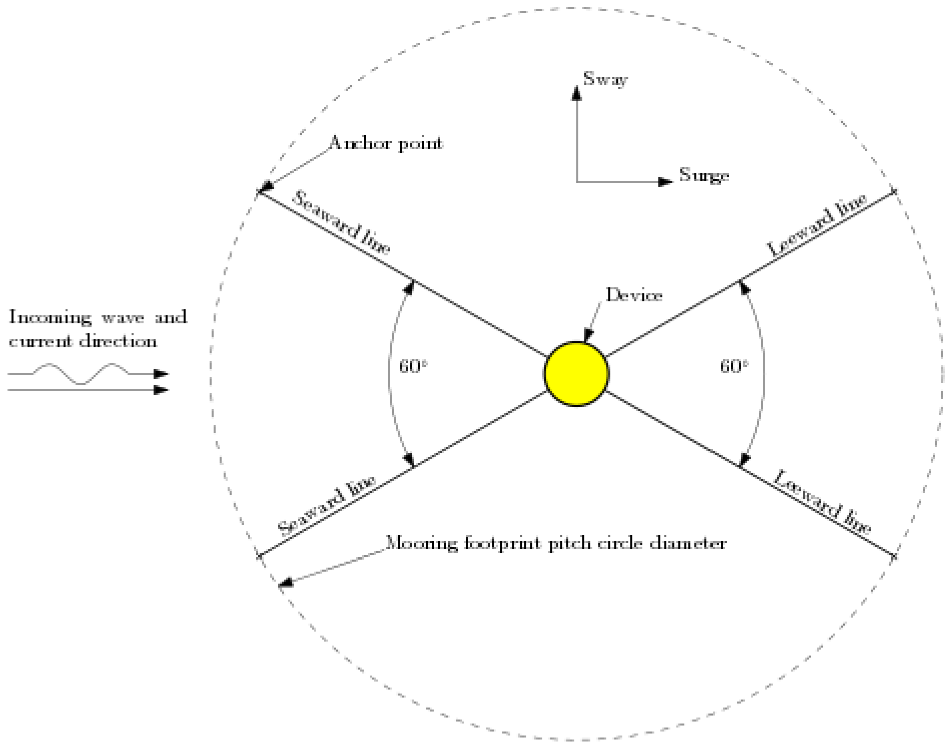


Figure 72: Plan view schematic of the device showing main attributes of the M&F system (source: TTI).

Table 14: Scenario specific parameters (S: specified as part of the scenario, C: calculated, T: TTI, M: manufacturer's data, HMGE: Handbook of Marine Geotechnical Engineering [99], DNV1: DNVGL-RP-C205 [84], DNV2: DNVGL-OS-E301 [4])

Category	Parameter	Value(s)	Unit	Source
General	Acceleration due to gravity	9.80665	m.s^2	S
	Seawater density	1025.0	kg.m^-3	S

Category	Parameter	Value(s)	Unit	Source
	Simulation build-up period	100.0	s	S
	Simulation length	3600.0 (max)	s	S
	Simulation implicit time step	0.06 (default), also adaptive	s	S
	Total number of simulations	5274 (synthetic), 1429 (chain)	N/A	S
Site details	Water depth	25.0 - 100.0	m	S
	Anchor footprint	100.0 - 1000.0	m	S
	Wave spectrum	JONSWAP	N/A	S
	Peakedness factor	1.0	-	S
	Wave direction	0.0	deg	S
	Significant wave height	12.0	m	S
	Peak wave period	18.0	s	S
	Current velocity	1.0	m/s	S
	Current direction	0.0	deg	S
	Current depth profile	1/7 power law	N/A	S
	Soil type	Medium Sand	N/A	S
	Seafloor friction coefficient	0.5 (normal and axial)	-	HMGE
Device	Diameter	7.6 - 27.9	m	C
	Displacement	100.0 - 5000.0	te	S
	Draft	2.2 – 8.0	m	C
	Height	4.3 – 16.0	m	C
	Ixx, Iyy	514.7 - 349280.9	te.m^2	C
	Izz	715.0 - 485228.5	te.m^2	C
	Assumed VCG at the keel	2.2 – 8.0	m	C
	Number of Morison elements	10	N/A	S
	Drag coefficient (normal)[30]	0.355-1.199	-	DNV1
	Drag coefficient (axial)	0.89	-	DNV1
	Added mass coefficient (normal)	0.479-0.993	-	DNV1
	Added mass coefficient (axial)	1.382	-	DNV1
Mooring system geometry	Number of lines	4	-	S
	Seaward/leeward line azimuth angles	60.0	deg	S
	Pretension level	5.0 (chain) or 20.0 MBL (rope)	% MBL	S
	Line drag coefficient (normal)	1.6 (rope), 2.6 (chain)	-	DNV2
	Line drag coefficient (axial)	0.0 (rope), 1.4 (chain)	-	DNV2
	Line added mass coefficient (normal)	1.0 (rope and chain)	-	DNV1
	Line added mass coefficient (axial)	0.0 (rope and chain)	-	DNV1
Materials	Steel density	7851.1	kg.m^-3	M
	Concrete density	2400.0	kg.m^-3	M
	Cost	5.7 (steel), 0.24 (concrete)	£.kg	T/M
Components	Number of available component sizes	114 (chains including Grades 3 and 4)	N/A	M

[30] The device drag and added mass coefficients were estimated using the empirical formulae found in DNVGL-RP-C205 [84] assuming a regular wave of height 12m and period equal to 18.0s and water depth and body dimensions specific to cases considered.

Category	Parameter	Value(s)	Unit	Source
		48 (ropes) 182 (drag anchors) 10 (vertical lift anchors) unlimited (gravity anchors)		
	Diameter	Component dependent	m	M
	Axial stiffness	EA/BL = 4 and 8 (ropes), diameter dependent (chains)	kN	S/C
	Linear dry weight	Component dependent	kg.m^-1	M
	Minimum break load (MBL)	Component dependent	kN	M
	Effective diameter	Calculated	m	C
	Failure rate	0.09225 (ropes) 0.02992 (chains) 1.18721 (anchors)	failures.10^-6 hours	T
	Cost	Component dependent	£/m	T/M
	Mooring partial factors of safety	1.1 (mean component), 1.5 (dynamic component)	-	DNV2
	Foundation factor of safety	1.5	-	HMGE

From the assumptions listed above the analysis presented in this study has its limitations. For the benefit of the reader uncertainties regarding this approach are listed, along with their potential impact and recommendations for future analyses in Table 15. Whilst these shortcomings are acknowledged, the purpose of this part of the Landscaping Study is to present indicative results of how M&F design choices could influence a system's LCOE instead of being a detailed design exercise which explicitly follows standardised approaches. Furthermore the authors recommend that developers engage with mooring specialists early on in a project in order to carry out the detailed design of WEC moorings required for certification.

Table 15: Uncertainties in the analysis and potential impacts in the context of MRE M&F systems.

Uncertainty	Error(s)	Impact(s)	Recommendation(s)
Estimation of design mooring loads with only one design sea state and one short realisation of this sea state.	Standards specify an appropriate number of design environmental conditions typically using design contours based on joint probability distribution of significant wave height and peak wave periods. These include extreme responses estimated using extreme distributions.	Maximum device responses and/or line tensions may not correspond with highest sea-state as one or more natural periods may be excited in different conditions.	To avoid the M&F system from being under-designed, carry out full set of design cases once initial design filtering has been conducted.
	Standards specify an appropriate number of environmental	Maximum device responses and/or line tensions may not correspond with	

Uncertainty	Error(s)	Impact(s)	Recommendation(s)
	condition combinations.	collinear environmental directions (e.g. the influence of cross-wind and/or current).	
	Standards specify an appropriate duration for each design case.	Maximum device responses and/or line tensions may occur during other time intervals if simulation duration is less than recommend.	
	For each design sea state considered, standards recommend that multiple realisations are tested and that the value of the most probable maximum (MPM) of a response variable of interest is estimated by fitting an extreme value distribution to the maxima from the set of tests.	Estimated maximum response variables (e.g. line tension or excursion) could be being underestimated.	
Empirical model of the device hydrodynamics.	Model is not validated against physical prototype.	Device motions may be smaller/larger than simulated leading to over-/under-conservative M&F system.	Based numerical analysis on small- or large-scale model tests.
Constant stiffness properties to model axial tension-elongation behaviour of nylon lines.	Non-linear, time-dependent behaviour of synthetic lines not accounted for.	Simulated mooring system stiffness likely to differ from actual behaviour leading to different line tensions and device motions.	Near future: Carry out sensitivity analysis according to common modelling approaches. Future: Utilise more detailed synthetic rope models.
Standard continuum mechanics modelling of chain.	Mechanisms such as out of plane bending (OPB), hocking etc. not accounted for.	Service life may be shorter than expected if these mechanisms occur.	Determine likelihood of occurrence and design for avoidance.

Uncertainty	Error(s)	Impact(s)	Recommendation(s)
Nonlinear wave loading of the device (e.g. high and low wave frequency loads).	Natural frequencies of the system being at wave frequencies other than those analysed.	Possibility of resonant responses not being identified.	Identify natural frequencies of the system as part of system design.
VIV can be an issue for taut moorings with fibre ropes.	Standards specify that this should be considered.	A different set of (potentially damaging) load conditions.	Determine likelihood of occurrence and mitigate effects if relevant.
Design limit states other than ULS not considered.	Typically ALS and FLS analysis also conducted.	Mooring system may be under-designed if: i) one line fails and ii) in terms of fatigue performance.	Carry out analysis will all limit states recommended by the standards.
Applications of factors of safety in codes for novel components.	Specified factors of safety generally presume a level of understanding of component behaviour.	Mooring system may be under-designed for design cases.	Conduct physical testing to reduce uncertainties in component performance.
Influence of pre-tensioning on device draft	The same level of pre-tensioning was used, resulting in different device drafts.	Different levels of device loading possible.	Acknowledge impact when comparing different mooring systems and device scales.
PTO system not modelled	Influence of PTO system on device and mooring system response not considered.	PTO system could significantly alter the response characteristics of the device and loads experienced by the mooring and/or foundation system.	Take steps to try to represent PTO system in the numerical model.
Device excursion limits not imposed	Devices with a permanent connection (e.g. power export cable) will have excursion limits.	Mooring systems which allow large device excursions identified by algorithm.	If relevant impose excursion limits.

Selection of Rope Stiffness

The case studies included a comparison between the use of chain and synthetic mooring lines.

As introduced in Section 3.10.2 there are two common approaches to modelling the stiffness of synthetic ropes in commercial software such as Orcaflex including using i) a simple linear value (i.e. secant stiffness) or ii) a single non-linear load-strain curve. It is not possible to directly account for hysteretic damping in Orcaflex and therefore it is not considered in this analysis.

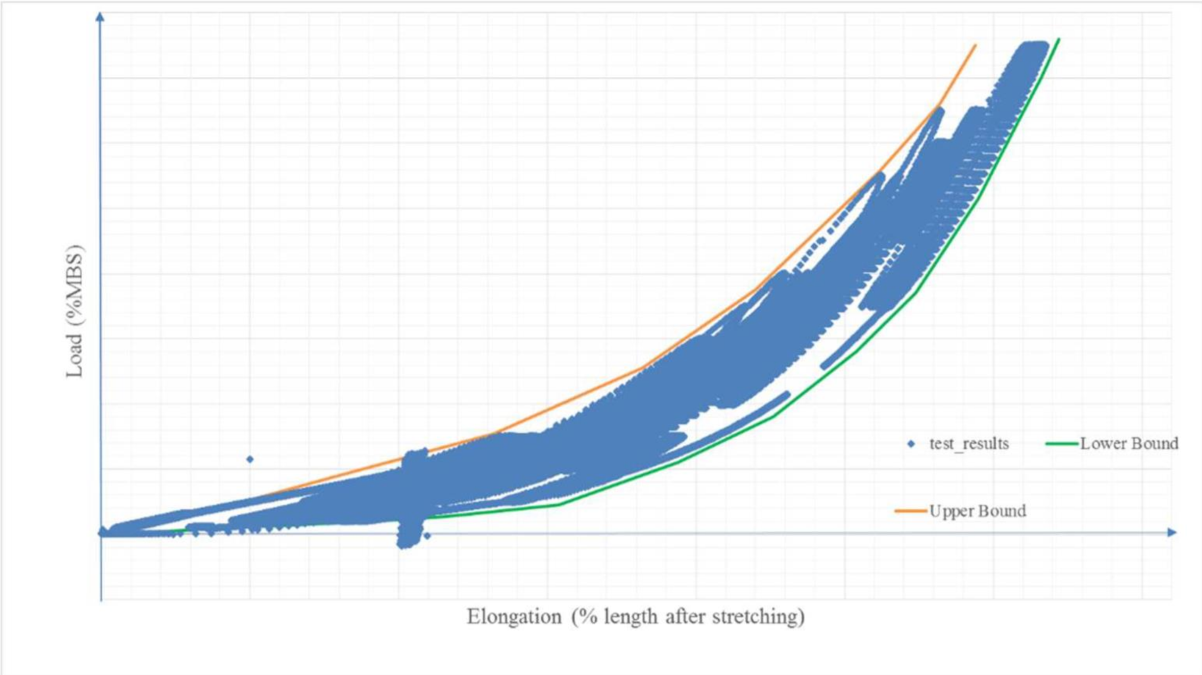


Figure 73 Load-elongation measurements for a nylon rope sample subject to tension-tension cycling at a prescribed tension range for several mean load levels (source: TTI).

Two sets of synthetic lines were used for the case studies, each identical (in terms of mass, buoyancy and hydrodynamic parameters) apart from their axial stiffness. In TTI's experience, the stiffness curve of a synthetic mooring line scales with the Minimum Break Load (MBL) of the line. For this study, a linear relationship between rope tension and extension has been assumed. This is a simplification of the non-linear load-extension behaviour of most synthetic ropes however it provides a good approximation of the stiffness without impacting on the setup and processing time of the simulation [80] and is applicable when there is reasonable linearity over the operating load range of interest [14]. The chosen values define the axial stiffness (EA) for the ratio of EA/BL.

The axial stiffness values used in the case studies have been based on testing of a nylon line completed by TTI Testing (Figure 73). These results showed a range of EA/BL values could be used to approximate the stiffness of the rope at different elongation values, results ranging from an EA/BL of 2 up to 16. It should be noted that these results are based on a bedded-in rope (i.e. post-installation), and therefore are stiffer than a new wet rope. The values of 4 and 8 used in the case studies were selected as they gave a reasonable approximation of the normal range of operation of the materials.

Note as the intention of the case study is to explore the benefits of greater compliance rather than the specific benefits of greater compliance of nylon lines, the axial line stiffness in the simulations reported here has been modelled using nylon-like axial stiffness values (selected as described) rather than using a synthetic line axial stiffness model of the type recommended in current industry guidance (e.g. the model from DNVGL-RP-305 described in Section 3.10.2).

Readers designing moorings using nylon components are recommended to either follow current industry guidance (such as given in DNVGL-RP-305) or to seek advice from specialists on the most appropriate method to model the axial stiffness of these components.

Readers designing moorings using synthetic ropes should also be aware that more detailed approaches to modelling their axial load-elongation than those advocated by current industry recommendations are currently under development (e.g. on the Syrope and SynMaRE projects, see also Section 3.10.2). Some of these aim to model explicitly the hysteretic effects which are a feature of the load-elongation behavior of synthetic lines (described in Section 3.3.3).

6.2.2 MODELLING PROCESS

Referring to Figure 74 the analysis process includes the following main stages:

a) Initialisation of system based on scenario parameters and available components in the database occurs in the *Mooring sub-module.* The smallest size component is used first.
b) Model building using the OrcFxAPI.
c) Static simulation followed by dynamic simulation for up to 3600.0s. This is clearly shorter than the recommended 3-hour sea-state (see Section 3.10.2), however, use of shorter simulations provides a means of efficiently filtering out unsuitable designs. The simulations were stopped prematurely to reduce overall processing time if the characteristic tension calculated by the DNV partial safety factors approach in ultimate limit state (ULS) [4] is greater than the required line component's MBL. The characteristic tension at failure is used to identify higher capacity components for the next run[31]. Therefore it is not always necessary to check the suitability of every component in the database and this can reduce overall run times.
d) Once the ULS check is satisfied, the maximum anchor tensions are passed to the *Foundation sub-module.*
e) The CAPEX and mean time to failure (MTTF) of the mooring lines are calculated by the module.
f) Design of the anchor type specified for the scenario (drag embedment, gravity foundation or vertical load anchor) was post-processed using the results from the optimiser tool. A check is made to ensure that the holding capacity of the anchor is sufficient (including a factor of safety).
g) The CAPEX cost of the anchor was then summed with the other costs from the module prior to further analysis of the results.

[31] Other optimisation strategies exist, such as adding extra line(s) for load sharing (and redundancy) whilst maintaining mooring system compliance. One consequence of the optimisation strategy used in this study is that unless higher material grades are available (i.e. chains) moving to higher capacity components can increase the stiffness of the mooring system which may not be desirable in terms of device motions.

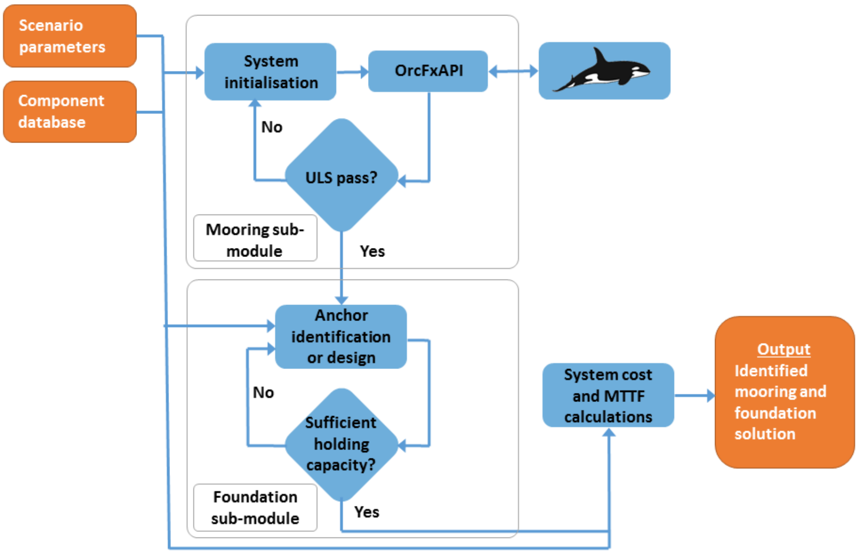


Figure 74: Simplified work-flow used in the analysis. The Orca symbol represents interaction with the Orcaflex software via the OrcFxAPI (source: TTI).

Ultimate limit state (ULS) considered. The mooring and foundation module is also capable of carrying out accidental limit state (ALS) analysis with one line removed but was not considered for this study.

6.2.3 CAPEX Calculation

- Chain costs use a per-unit-length rate (£/m). Line lengths trimmed as a post-processing step.
- Synthetic rope costs use a per-unit-length rate (£/m) and termination cost for the splice which is dependent on rope capacity.
- Line connecting hardware (e.g. shackles, swivels etc) are not considered.
- Drag embedment anchors and VLAs use unit costs.
- Gravity anchor costs are based on required material volume and hence bulk material costs.
- The costs mentioned above are based on values used in-house by TTI. Economies of scale are not considered in this analysis.
- For the purposes of this study it is assumed that nylon or equivalent synthetic with a softer EA/BL of 4, would have a similar unit cost to parallel strand nylon (EA/BL = 8).

6.2.4 MTTF Calculation

Failure Rate Data

While a number of MRE device sea-trials have been conducted mainly for proof of concept, at the time of writing there have been no long-term (+5 year) MRE deployments from which it is possible to derive generic failure rate statistics. As a result, the failure rates of mooring line components used in the MTTF calculated were derived by TTI from reported failures of oil and gas production and non-production mooring systems. The calculated annual failure rates of 2.62 x 10-4 failures/annum and 1.16 x 10-4 failures/annum are used for chain and synthetic rope respectively (see Section 3.3.4). While different failure rates are provided for different components; it is not possible to scrutinise the mode of failure in each case (again due to a lack of reporting detail).

The failure of an anchor to provide a secure mooring line termination point can be classified in two ways: i) material or structural failure resulting in the loss of station-keeping contribution from the respective mooring line ii) dragging of the anchor resulting in an alteration of station-keeping ability of the mooring line and possibly entire mooring system. The former case is an issue for the manufacturing Quality Assurance as well as ensuring that an adequate design has been specified. In the latter case, the anchor may re-embed, but it is likely that this change in position would have a knock-on affect on mooring system performance (i.e. the overall stiffness of the mooring system or the possibility of 'out-of-plane' loading). Furthermore, accurate positioning of anchors is notoriously difficult to achieve in practice and reliant on a post-installation survey. In general, there is less information available for anchor failure events, especially material or structural failures and failures may be hidden in various reports of 'mooring line broke', or 'failed'. The survey indicates that mooring and anchoring planning and deployment procedures need to be further refined - including more detailed on-site examination of a mooring spread after it had been installed. As mentioned in Section 3.3.4 anchor failure rates are not readily available and for this reason a target level of 1.0 x 10^{-4} failures/annum is used, corresponding to the Recommended Practice of the American Petroleum Institute guidelines [23].

It is not clear at this stage how failure rates for MRE mooring and foundation systems are likely to differ from the oil and gas values mentioned above. Utilising learnings from the offshore industry (in addition to component developments) should enable systems to be developed with lower failure rates. However, this is reliant on reliability data sharing within the MRE sector and assumes that such knowledge can be readily adapted for MRE applications.

Calculation Procedure

In this study the mean time to failure (MTTF) is estimated using the derived failure rates introduced in the last section under the assumption that there are a constant rate of random failures which tend to occur during the 'useful' or operational life of the component or sub-system (i.e. failures can be expressed by exponential probability distribution functions [65]). The calculation method accounts for the relationship hierarchy between components and subsystems, thus for a single mooring line comprising *n* components each of which has a failure rate λ_i connected in series (e.g. a chain connected directly to an anchor):

$$MTTF_{line} = \frac{1}{\sum_{i=1}^{n} \lambda_i} \quad (1)$$

In mooring design Accident Limit State analysis [4] is carried out to ensure that systems with multiple lines can still function if the failure of one line occurs. In reliability analysis terms the provision of redundancy can be represented as an '*m of n*' system (where *n* is the number of mooring lines and *m* = *n* – 1).

$$MTTF_{system} = \frac{1}{\lambda_{eq,line}} \sum_{m}^{n} \left(\frac{1}{m} + \frac{1}{n}\right) \quad (2)$$

where:

$$\lambda_{eq,line} = \frac{1}{MTTF_{line}} \quad (3)$$

6.2.5 Outputs and Quality Assurance Checks

Quality assurance 'sense' checks were carried out at each step of the automated calculation procedure to ensure that the Orcaflex models were being set up correctly and that components were being selected as expected. Cross-checking was also carried out between the results for different scenarios. The main results are listed in Table 16 some of which were used for planning of which vessels would be required for installation and subsequently the time required for transit and installation on site.

To provide a fair comparison between the chain and synthetic rope results 'unused' chain (i.e. defined as any chain which remains on the seabed during the simulation) was trimmed (thereby reducing the mooring footprint) and the equipment costs subsequently updated. The length of line resting on the seabed of the four lines was logged during each simulation, and the minimum length used to determine the potential trimmed length.

Table 16: Outputs.

General outputs	Outputs used for installation planning
Component list	
System cost System mean time to failure (MTTF) Maximum line and anchor tensions Maximum device excursions Characteristic tensions (partial safety factor approach) Simulation duration (full or partial)	Dry component masses Component dimensions Line length (after adjustment for pretension)

Table 17 lists the number of scenarios processed and total number of Orcaflex simulations required to satisfy ULS criteria for each scenario set. By definition a 'completed' scenario represents one with an identified mooring and foundation system; a full breakdown of which can be found in the Appendices. The differences in elapsed time reflect the number of Orcaflex simulations carried out, rather than the time required for anchor design (which is relatively quick). Reviewing the output files it would appear as though the different number of Orcaflex runs is due to variations occurring from simulation to simulation, particularly those which are chaotic (i.e. the largest device scale in shallow water). Such device responses and mooring tensions may be physical or numerical phenomena. Furthermore, all dynamic solvers are susceptible to instability and response divergence (e.g. [114]) and non-linear responses are likely to be a particular issue for equipment which is designed to be highly responsive such as wave energy devices [115]. This highlights the need to carry out sensitivity analysis of device response and mooring system tension through using: i) multiple environmental condition cases, ii) a sufficient simulation length and/or multiple simulations with different inputs parameters (such as wave phases) to ensure that a wide enough range of device responses and the most probable maxima of mooring line tensions are captured [90].

Table 17: Number of scenarios processed.

Line type	Anchor type	Number of planned scenarios	Number of completed scenarios	Number of required Orcaflex runs	Elapsed time [hours][32]
	DEA	52	41	716	41.4

[32] Workstation specifications: Intel® Core™ i7-4790 Processor @ 3.6GHz (8 CPUs) with 16GB of RAM. Note: parallel processing was not used.

Chain catenary	GBA	52	41	713	40.3
Taut synthetic	DEA	104	88	1759	60.5
	GBA	104	88	1767	69.8
	VLA	104	88	1748	53.7

To check if the component selection process was adequately identifying suitable components, the utilisation factor (defined as characteristic tension/component BL, [4]) was calculated for all of the scenarios. Plotted in Figure 75 the utilisation factors are in the range of 80-100%, demonstrating that the identified solutions are close to optimal. Some outliers less than 80% are noted for a few of the Grade 3 chain and synthetic rope cases suggesting that while these solutions comprise components with sufficient strength, they are potentially over-engineered. This could be an artefact of the logic used in the modelling process, which identifies replacement components based on the characteristic tension logged during the last failed run. Rather than attempting to assess every single component size in the database the ability to skip sizes reduced overall processing times. However, interim component sizes (which typically have lower linear weights and hence contribute to lower system pretensions) may be adequate. A heuristic approach could be more efficient in terms of component selection (e.g. [116, 117]).

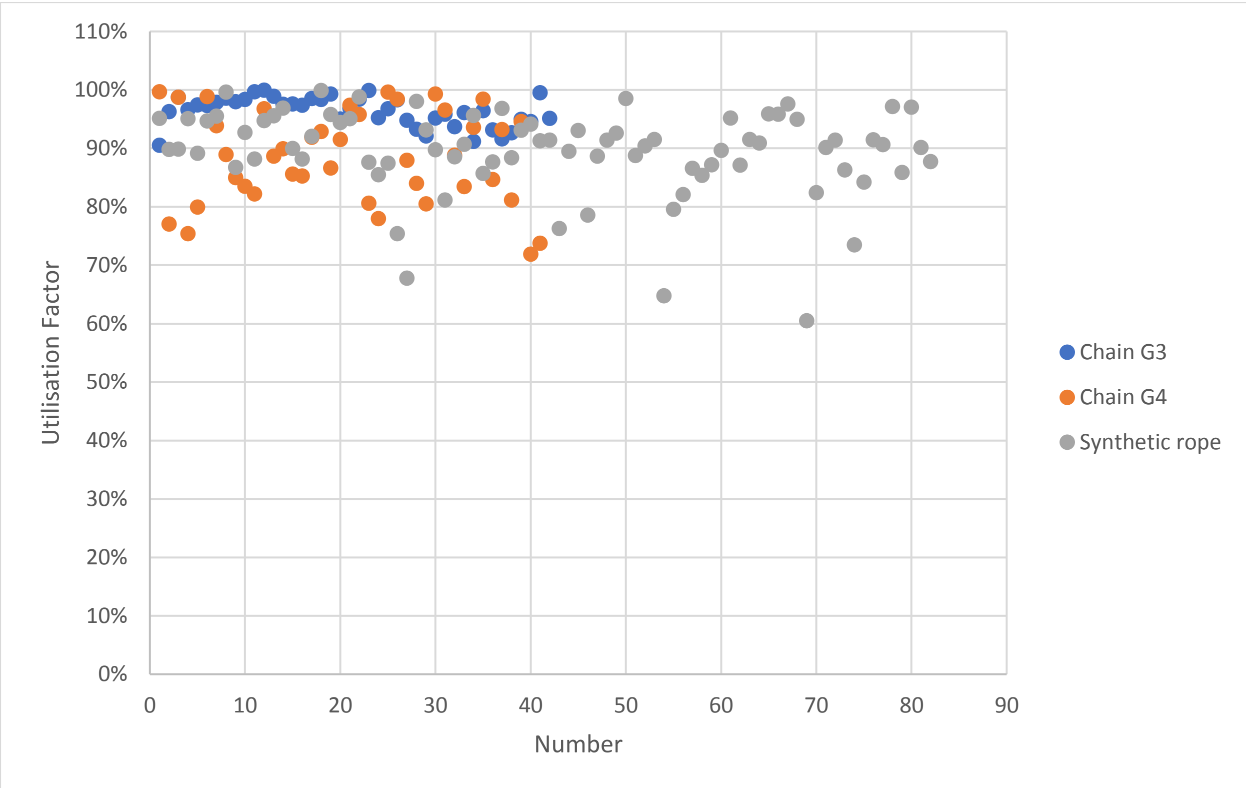


Figure 75: Utilisation factors of identified line components (G3 and G4 denote Grade 3 and Grade 4 chains respectively).

6.2.6 Installation Costs

The cost of installation of a mooring system is dependent on the type and size of vessel hired and the number of days hire required. The tool calculates an estimated cost of vessel hire, however, the cost data used would require regular updating as cost varies greatly with the demand, primarily from the Oil and Gas industry.

Vessel Selection

The selection of the vessel has been based on the winch line pull or the lifting capacity depending on the requirement of the defined anchor. Winch line pull was used for Drag Embedment Anchors (DEA) and Vertical Plate Anchors (VLA) whereas the lift capacity was used for the Gravity Based Anchors (GBA).

Alongside the aforementioned parameters, the database also provides values for the deck space, transit speed, cargo capacity and day rate. These parameters are used in the estimation of the hire time required to complete the installation.

Deployment Time

The deployment time has been estimated based on the following parameters:

- Vessel Speed
- Storage area of vessel
- Distance to Site
- Type and size of anchor
- Number of mooring legs
- Mooring line material

The time required to install the mooring system is driven from two sources; the time required on site to deploy the mooring systems, and the time required to get to and from the deployment site.

The time taken to deploy the mooring lines is dependent on the type of anchor, and the number of lines to be deployed. Different deployment rates were assumed for GBAs, DEAs and VLAs, this includes consideration for the hook up of the device to the mooring system.

The time taken to travel to and from the deployment site is dependent on the distance to port, the speed of the vessel and the number of trips required. The Excel tool assumes that only one vessel is working on a deployment at a time. The chosen vessel may not have the storage capacity for all the required anchors and mooring lines to be installed in a single trip and therefore may have to make multiple trips to and from the deployment site.

The deck area of the vessel was used as the measure of the available storage area, this was seen as being the most common, easily used parameter between vessels. However, anchor handling vessels (AHVs) are known to have chain locker facilities located underneath the deck thus increasing the available storage space of these vessels, but also complicating its measurement.

Based on a review of Maersk Supply fleet it has been assumed that the volume of the chain lockers for a range of AHVs can be estimated[33] as the deck area multiplied by 1m. When calculating the space

[33] For the range of vessels considered, the estimate was based on the chain locker area divided by the deck area, the average of which is approximately 1m.

requirement for storage space for a single leg of the mooring system on an AHV the larger of either the percentage deck space required for the anchor or the percentage of the chain locker required for the chain was used. All other vessel types assume that the chain is flaked on the deck.

Synthetic lines are assumed to be stored on reels on the deck of the vessel, the area required for this storage is much smaller than that of the same length/strength of chain. The area required is calculated based on standard reel sizing formula.

The deck footprint requirement for the anchors is based on the sizing output from the DTOcean tool in the form of the length, width and height of the anchor.

Using the deck area required for a single leg of the mooring system and for the whole mooring system the tool then calculates the number of trips required to transport the full mooring system to the deployment site. This, in combination with vessel speed and distance from port to deployment site, gives the travel time required.

The total hire time required for a deployment is therefore the sum of the time at site deploying the anchors and lines, the travel time from port to site, the time taken to hook up the mooring system to the device and the mobilisation and de-mobilisation time at the start and end of vessel hire (assumed two days in total). In addition to this the tool considers a statistical weather window allowance on vessel hire of 75%, 60% and 75% for AHV, Multicat and Crane respectively.

6.3 Mooring Compliance Study Results

6.3.1 Influence of Compliance on Line MBL with Device Scale

Figure 76 indicates the benefit of compliance across the three WEC device scales of 100T, 1000T and 5000T. Referring to Figure 72, maximum surge excursions are included in this plot and Figure 77 to Figure 84 for reference and are discussed in Section 6.3.6. This comparison is limited to the 100m water depth and 1000m footprint scenario as chain cases for 5000T displacement failed to satisfy the design criteria for any of the shallower water depths. The plot highlights the benefit of a taut mooring system with axial compliance over chain catenary in terms of the required component MBL across all device scales. For example, for 5000T WEC the required MBL is reduced from just under 11000kN to 2000kN when moving from a chain catenary to taut synthetic system (EA/BL = 4). However, the lower EA of the synthetic rope-based system combined with very large footprint would lead to large excursions which could be challenging in terms of exporting power via an umbilical. For the smallest 100T device a 1000m footprint is unlikely to representative and is adopted in Figure 76 for comparison purposes only. For 100T case, it may be more practical to accept higher mooring loads for a smaller footprint. The influence of footprint is addressed in more detail in Sections 6.3.2 and 6.4.3.

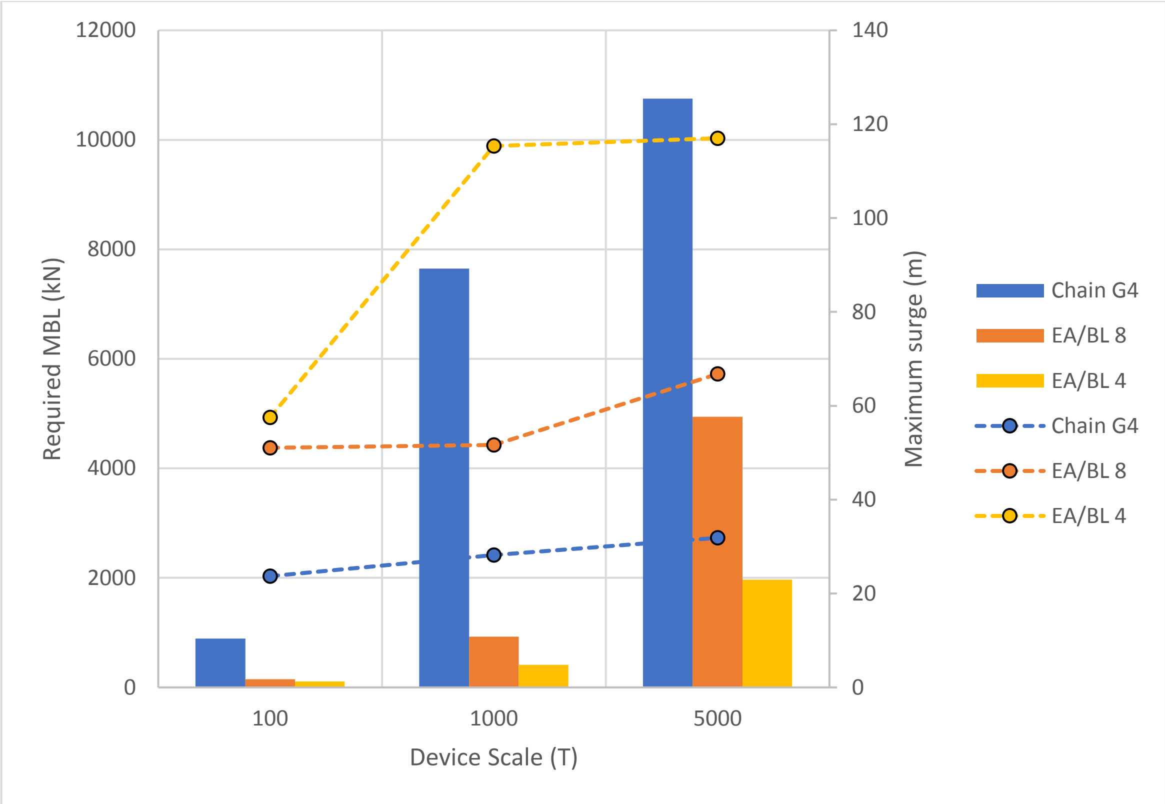


Figure 76: Required MBL (bars) and maximum surge excursions (markers) for a range of device scales and mooring line compliance in 100m water depth and 1000m footprint.

6.3.2 Influence of Footprint on Line MBL for Line Type

While the high axial stiffness of chain relies on catenary for compliance, taut synthetic mooring lines can provide compliance if low axial stiffness ropes are selected. The overall compliance of synthetic rope is a function of the rope material properties, construction, usage and length. Therefore compliance is a function of footprint, axial stiffness and (in the case of chain catenary moorings) the wet weight of the chain. This comparison has been based on the 1000T buoy and a representative water depth of 75m has been chosen. The trends were shown to be similar across the other water depths.

From Figure 77, it can be seen that rope stiffness and footprint are powerful levers for reducing mooring loads. For the synthetic rope cases the reduction in required MBL can be seen to be disproportional with footprint (noting a lower MBL line will have a lower axial stiffness). Generally, having a greater mooring system compliance leads to lower line loads, however, this is not always the case. It should be noted the phasing of the device motion compared to wave loading can vary for each case, and due to system dynamics, it is possible that a softer mooring produces a higher peak load. In terms of chain line loads (represented as required MBL) Figure 77 shows diminishing returns in increasing footprint size for the chain-based moorings. Analysis of individual footprint cases showed that excess chain was being left on the seabed under peak loading conditions for footprints larger than 500m.

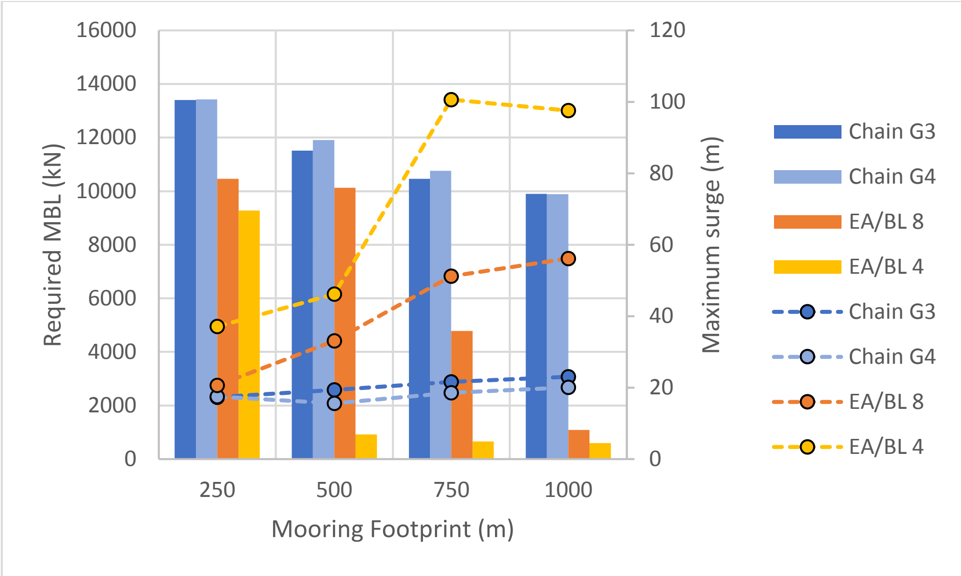


Figure 77: Required MBL (bars) and maximum surge excursions (markers) for a range of mooring footprints and mooring line compliances in 75m water depth and a 1000T buoy.

6.3.3 Influence of Water Depth on Line MBL with Line Type

WEC developers may target particular water depths or bathymetry profiles for various reasons and perceived benefits, which can include performance, distance from the grid, anchor selection, access to suitable seabed conditions and mooring costs. Figure 78 demonstrates the influence of water depth on line MBL comparing chain with the two synthetic rope axial stiffness values for the 1000T displacement buoy and a footprint of 750m. The 100T buoy case was found to be less water depth sensitive due to its scale and hydrodynamic loading across the water depths (results not shown).

It can be seen from Figure 78 that there is a clear benefit of adopting a compliant system for all of the water depths considered, particularly 50m to 100m. This benefit is magnified when we also account for the lower unit cost of nylon for given MBL.

A limited number of solutions were found for the 5000T displacement buoy particularly for the chain cases in 25m water depth, suggesting that only the nylon option is feasible in this scenario. For the shallow water depth chain cases the optimisation process would tend to drive towards larger diameter and heavier chain with higher MBL, which would then stiffen the mooring system further and further increasing the peak loads leading to an unviable outcome (the dramatically named 'spiral of death'). The largest chain diameter considered was 177mm which is not practical for marine operations and has unit weight 0,686T/m (5000T in 75m water depth 500m footprint)

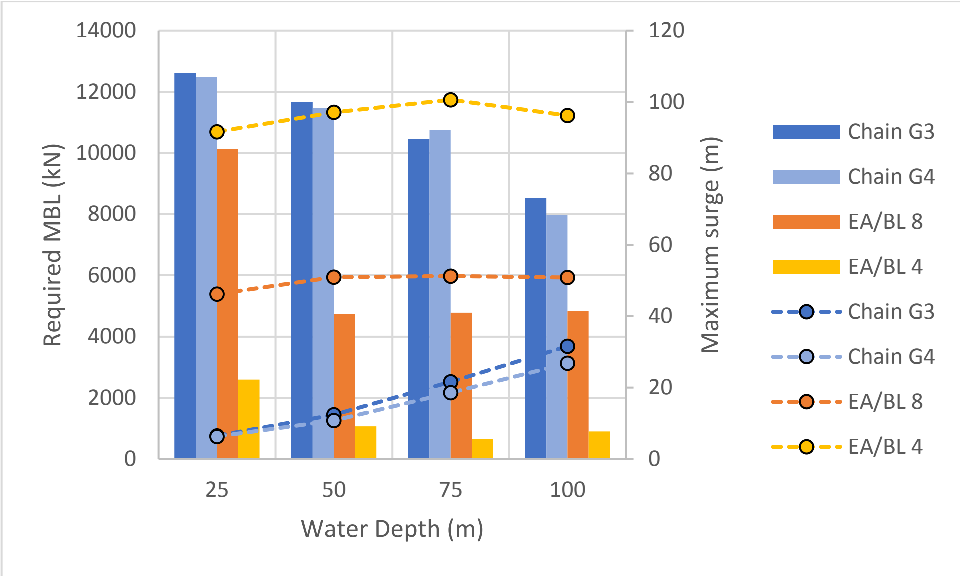


Figure 78: Required MBL (bars) and maximum surge excursions (markers) for a range of water depths and mooring line compliances with a 750m footprint and a 1000T buoy.

6.3.4 Impact of MBL Requirement on Dry Mooring Line Weight

The MBL requirement for both chain and nylon has a direct impact on the weight and ultimately cost of the mooring lines (note: 'weight' refers to the dry weight of the line herein). It is useful to look at this independently of foundation costs, which are addressed later in Section 6.4. The weight is important as this has a direct impact on how easy the lines are to handle and install and hence ultimately the LCOE.

Figure 79 compares the total mooring line weight for all four lines for the 100T buoy for 750m mooring footprint, comparing chain grades 3 and 4 with a nylon-based mooring line. It can be seen that the synthetic-based system has a much lower weight compared to the conventional chain systems for the four water depths studied. The increased compliance of the lower stiffness ropes (EA/BL=4) appears to result in lower line tensions and subsequently a lower required MBL rating (i.e. smaller and lighter ropes). As expected the specification of a higher grade chain leads to a smaller chain size and hence lower total line mass.

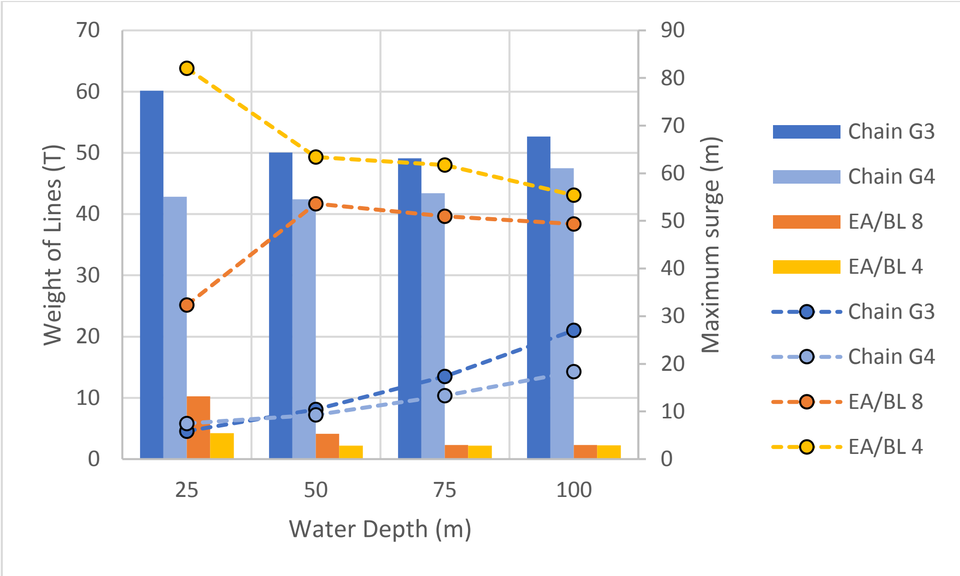


Figure 79: Total dry mooring weight (bars) and maximum surge excursions (markers) for a 100T buoy with a 750m footprint

Line weights for the 1000T buoy with a 750m mooring footprint are presented in Figure 80. Compared to the smaller device scale there is a much greater benefit in adopting synthetic-based system over conventional chain across all water depths considered. The weight of the chain is an order of magnitude heavier than synthetic based mooring, in some cases the total line mass required is 500T compared to less than 50T for the synthetic based case. Not only is the synthetic-based mooring system significantly cheaper but the weight would also have an impact on installation and recovery costs. This study considers two extremes of mooring system; chain catenary and taut synthetic. In practice, there may be hybrid moorings and different combinations which results in a total mass of line components which would fall within this range of ~50T to ~500T e.g. combinations of chain/wire, synthetic and shock absorber.

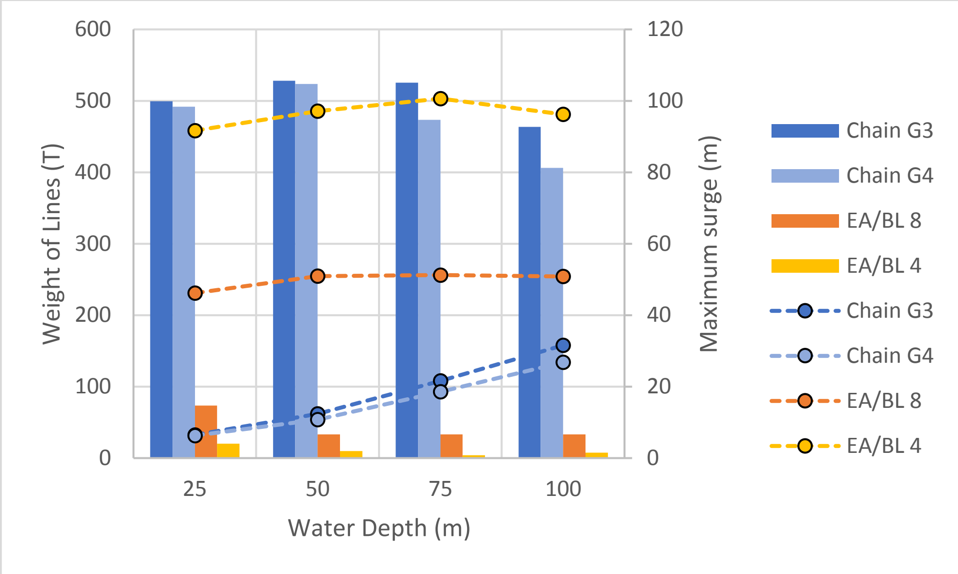


Figure 80: Total dry mooring weight (bars) and maximum surge excursions (markers) for a 1000T buoy with a 750m footprint.

Again for the 5000T device, the dry weight of the identified synthetic mooring systems was considerably lower than the chain systems for all water depths. For this device scale, there were some cases particularly for chain whereby a solution could not be achieved due to excessive line loads. Figure 81 compares a selection of cases where solutions were found for both synthetics and chain allowing a comparison to be made. For the chain cases, very large chain diameters were required which were in as large as 177mm bar diameter resulting in a very heavy total mooring line mass in excess of 1000T for the Grade 3 chain. What is interesting for 5000T case compared to the 1000T buoy is that compared to Grade 3, the higher MBL Grade 4 results in the lower loads, due to smaller bar sizes being selected. While the mass of the mooring system is significantly lower for synthetics, this comes at the compromise of increased buoy excursions.

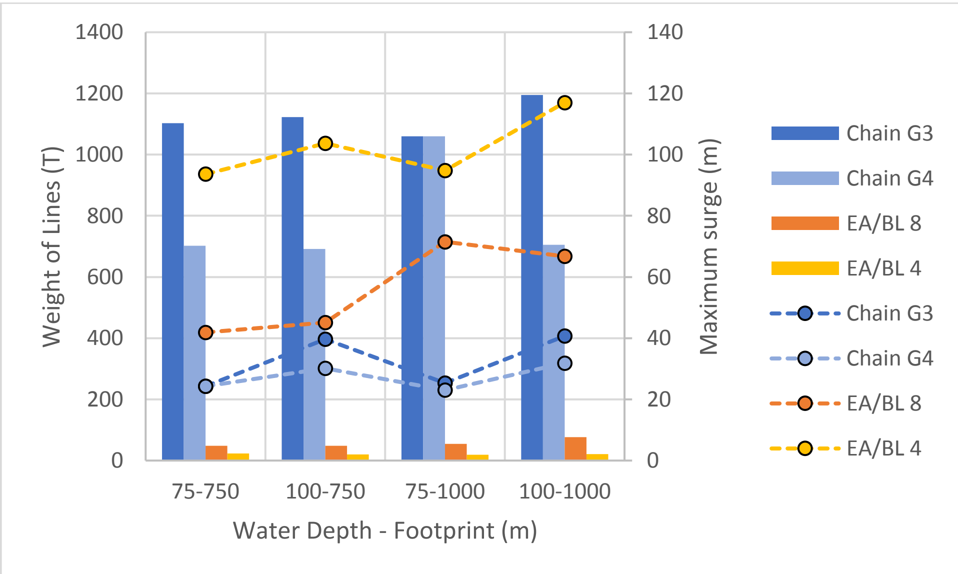


Figure 81: Total dry mooring weight (bars) and maximum surge excursions (markers) for a 5000T buoy with a 750m footprint.

6.3.5 Impact of MBL Requirement on Cost of Mooring Lines

In general there tends to be a combined benefit that lower loads and lower unit cost for a given MBL result in magnified cost benefit.

Line costs for the 100T device cases are plotted in Figure 82. With one exception (at 25m water depth) in general terms line costs are lower for the synthetic- based systems compared to the chain-based systems, particularly when the chain system costs are compared to the lower axial stiffness (EA/BL = 4) synthetic system. There is also a general trend of increasing disparity between chain and synthetic system costs with increasing water depth. For this device scale it is clearly evident that the use of Grade 4 chains is prohibitive, and for the scenarios studied, any cost-benefit in using higher strength chains is only evident for systems subjected to higher tensions (i.e. the larger device scales). The unit cost of chain (Grade 3) for a given MBL is approximately twice that of parallel strand nylon. Grade 4 chain is disproportionately more expensive for smaller chain diameters and in practical terms it is doubtful that large quantities can be economically ordered for anything below 54mm chain diameter (which for Grade 4 chain has an MBL ~3170kN).

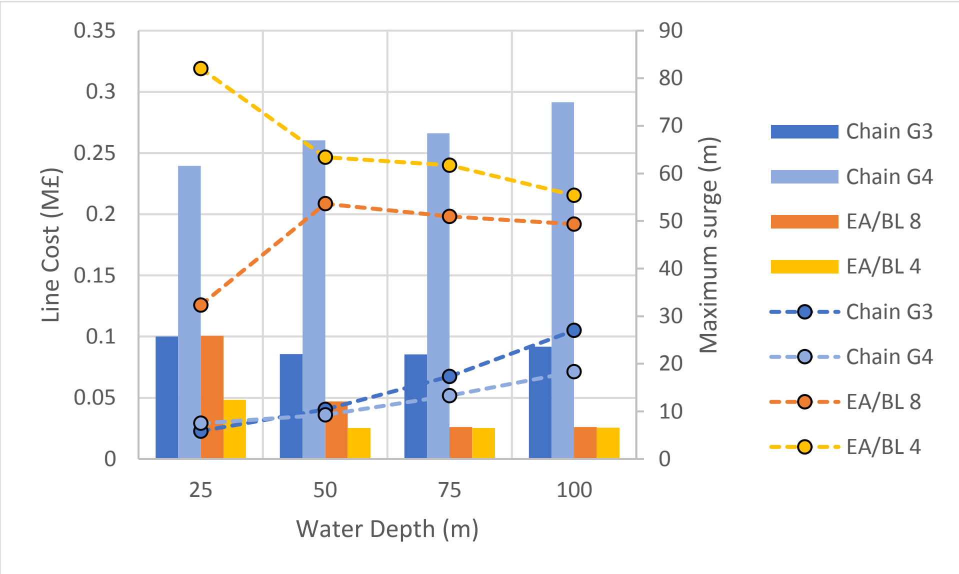


Figure 82: Total mooring line cost (bars) and maximum surge excursions (markers) for a 100T buoy with a 750m footprint.

Figure 83 demonstrates that for the 1000T case the total mooring cost for water depths of 50m, 75m and 100m tend to range from about £0.75M-£1.1M for chain to about £0.05M to £0.7M for synthetics. The cost benefit is less pronounced for the shallowest water depth of 25m and for this water depth the Grade 3 and stiffest nylon (EA/BL=8) are relatively close in total cost comparing ~£0.6M (nylon) ~£0.7M (Chain). This close agreement may be driven by the dynamics of the nylon case, resulting in shock loads. While nylon in this case appears to be less beneficial, there will be other savings in terms of weight and handle-ability for installation and fatigue resistance which impact on the cost of energy. Furthermore, it is clear from the results that for some cases chain is not viable for 25m water depth (e.g. 5000T buoy). For the 1000T buoy it is evident that lower break load Grade 3 is more cost-effective than Grade 4, which is the opposite for the 5000T buoy (Figure 84).

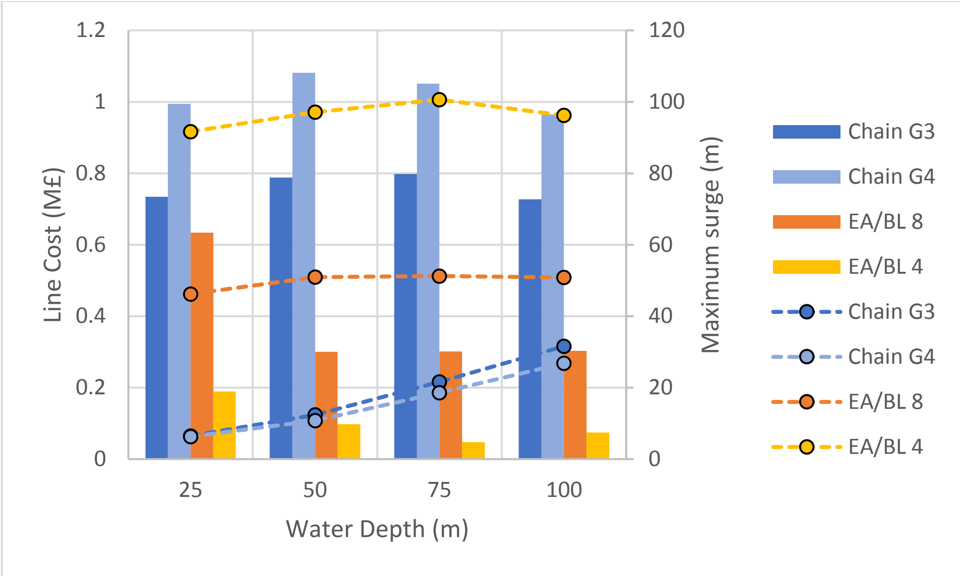


Figure 83: Total mooring line cost (bars) and maximum surge excursions (markers) for a 1000T buoy with a 750m footprint.

Figure 84 demonstrates that Grade 4 can be the most cost-effective option compared to Grade 3 for the higher loads associated with the 5000T buoy as a smaller component size can be adopted for Grade 4 compared Grade 3. There is a significant benefit in adopting synthetics where total line costs reduce from between £1.4M-£1.6M (chain) to £0.2M-€0.65M (nylon) and these benefits depend on water depth, footprint, grade of chain and axial compliance of nylon. Note that this selection of cases does not include solutions for chain mooring systems in 25m and 50m water depths as no practical solution was found in each case.

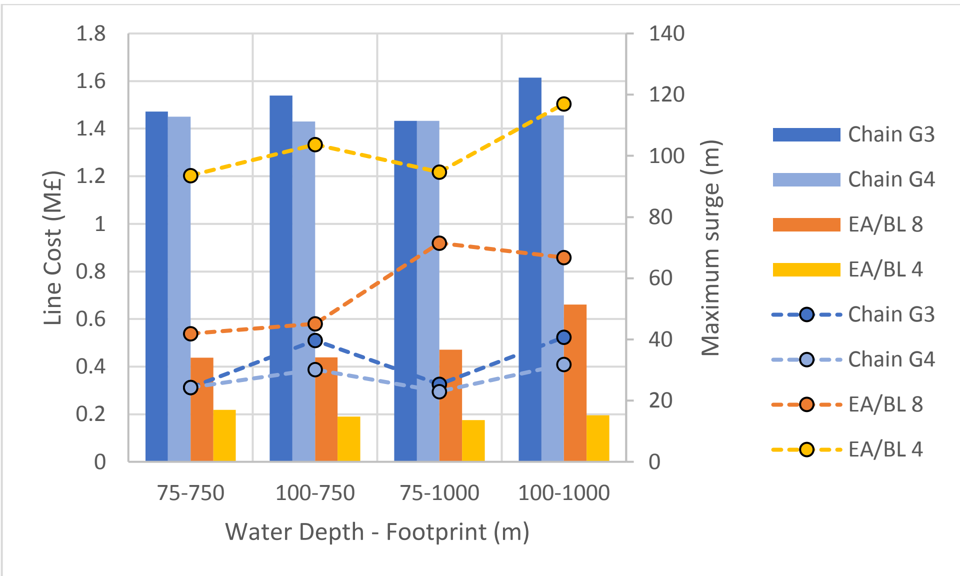


Figure 84: Total mooring line cost (bars) and maximum surge excursions (markers) for a 5000T buoy for several water depth and footprint combinations.

6.3.6 Comparison of Device Maximum Excursions with Total Line Costs and Characteristic Line Tensions

Although no constraints were imposed on device excursions in the case studies it is possible that a developer may wish to restrict the movement of the device to a particular envelope because there may be limits imposed by the dynamic power export cable and/or other nearby devices. With this in mind maximum surge displacements (in the direction of wave and current propagation) have been included in Figure 76 to Figure 85 for reference and are listed in Table 18. Maximum excursions in the sway direction were negligible (< 1m) and are hence not reported here.

Table 18: Maximum surge displacements for each device scale with corresponding water depths (d) and footprint (fp) radii.

	Maximum surge excursion [m]			
Device	**Chain G3**	**Chain G4**	**EA/BL 8**	**EA/BL 4**
BC1 (5000T)	40.7 (d100m, fp1000m)	31.9 (d100m, fp1000m)	71.5 (d75m, fp1000m)	138.4 (d25m, fp1000m)
BC2 (1000T)	36.3 (d100m, fp1000m)	28.2 (d100m, fp1000m)	71.4 (d50m, fp1000m)	115.4 (d100m, fp1000m)
BC4 (100T)	28.4 (d100m, fp1000m)	23.7 (d100m, fp1000m)	62.2 (d25m, fp1000m)	82.1 (d25m, fp750m)

Of the chain catenary cases studied the maximum surge excursion was 40.7m in the incoming wave and current direction (Grade 3 chain, 5000T device in 100m water depth with an initial footprint of 1000m). This contrasts the maximum surge displacements of the synthetic rope cases, which were up to 71.5m and 138.4m for the EA/BL = 8 and EA/BL = 4 rope stiffness values respectively[34]. In Figure 85 the synthetic rope cases with comparable maximum surge excursions (< 41m) are plotted against total line costs. There are no large device (BC1; 5000T) synthetic rope results presented in this plot because all of the maximum surge excursions were above 41m. For the two smaller device scales (BC2; 1000T and BC4; 100T) it can be seen that the line costs are generally lower for the synthetic rope cases. Considering the same set of results, maximum characteristic line tensions[35] are generally lower for synthetic rope cases and this is expected for more compliant line materials (Figure 86).

[34] The 138.4m max surge excursion was for the BC1 (5000T) device moored in 25m water depth with a footprint of 1000m. This represents a challenging design case that is probably impractical for most device developers.
[35] See Section 6.2.2 for a definition of this term.

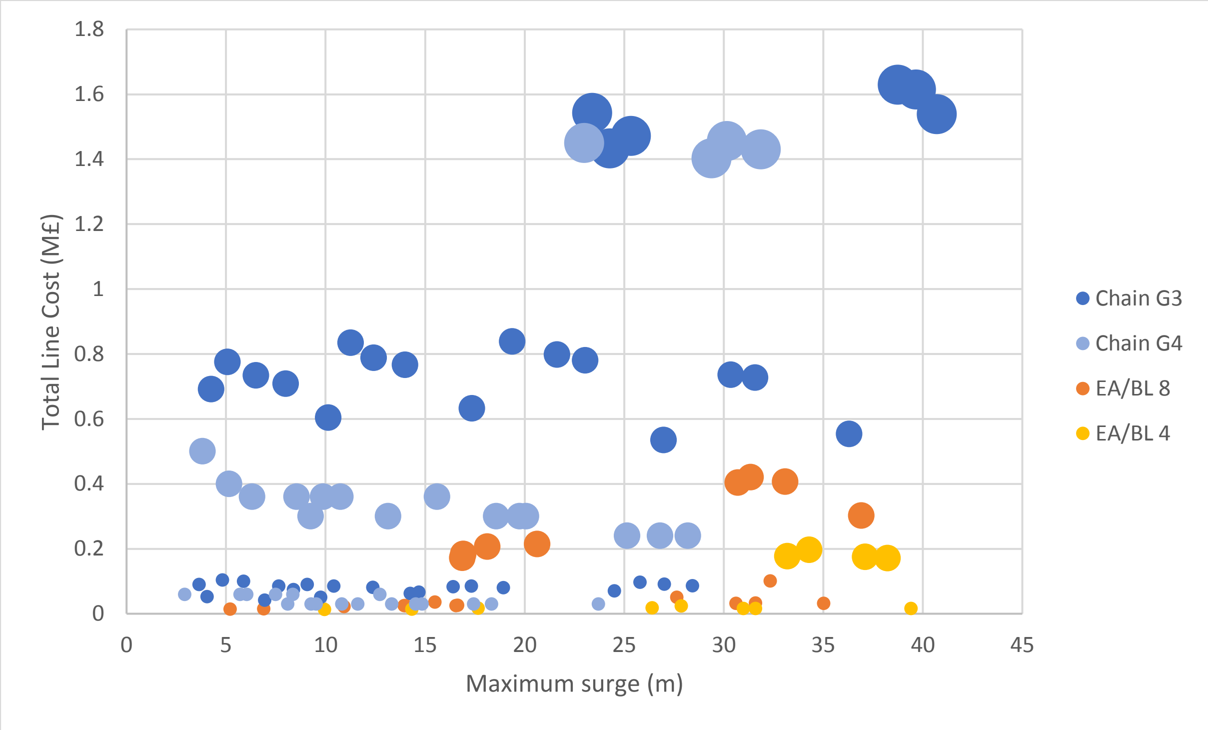


Figure 85: Total mooring line cost for several water depths and footprint combinations. Results are shown for cases where maximum surge excursions are below 45m. Marker size relates to device scale: BC4 (small), BC2 (medium) and BC1 (large).

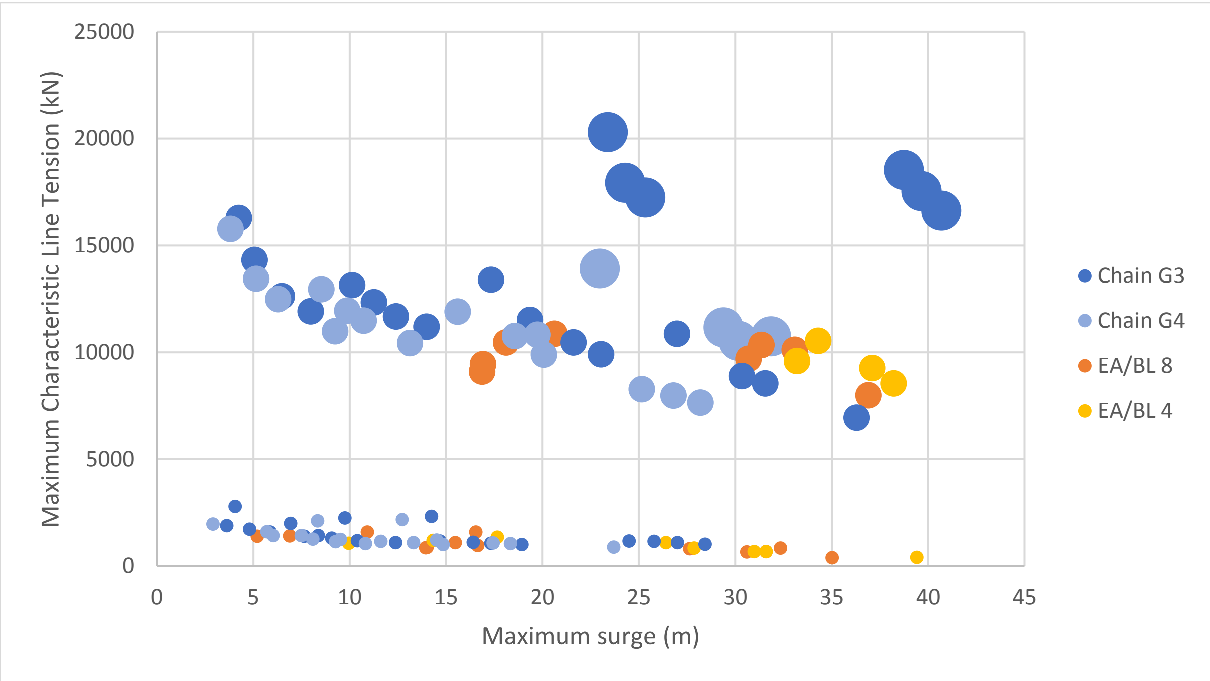


Figure 86: Maximum characteristic line tensions for several water depths and footprint combinations. Results are shown for cases where maximum surge excursions are below 45m. Marker size relates to device scale: BC4 (small), BC2 (medium) and BC1 (large).

The results presented in Figure 85 and Figure 86 are a selected of case studies with maximum surge excursions under 41m. Direct comparison from these graphs is not straightforward and for this reason maximum surge excursions, characteristic line tensions and total line costs for directly comparable cases are listed in Table 19 to Table 21. Due to increased compliance the maximum surge excursions of the most compliant synthetic rope cases (EA/BL = 4) are higher than all of the chain cases for the two smaller device scales (Table 19). However the nylon storm stiffness (EA/BL = 8) maximum excursions are similar to the Chain G4 cases in the deeper water depths (at low footprint-depth ratios), whilst maximum characteristic line tensions are lower in all but one case (BC2 device in 100m water depth and 250m footprint, see Table 20).

Table 19: Maximum surge excursions for comparable case studies.

				Maximum surge excursion [m]			
Device	**Water depth [m]**	**Footprint [m]**	**Footprint – depth ratio**	**Chain G3**	**Chain G4**	**EA/BL 8**	**EA/BL 4**
BC2 (1000T)	25	250	10.0	4.3	3.8	16.9	33.2
	50	250	5.0	10.1	8.5	16.9	34.3
	100	250	2.5	27.0	19.7	20.6	38.2
BC4 (100T)	25	250	10.0	3.6	2.9	14.0	27.9
	50	250	5.0	8.4	6.0	14.0	31.0
	100	250	2.5	24.5	14.5	15.5	39.4
	75	100	1.3	9.7	8.3	10.9	17.7
	100	100	1.0	14.2	12.7	16.5	26.4

Table 20: Maximum characteristic line tensions for comparable case studies.

				Maximum characteristic line tension [kN]			
Device	**Water depth [m]**	**Footprint [m]**	**Footprint – depth ratio**	**Chain G3**	**Chain G4**	**EA/BL 8**	**EA/BL 4**
BC2 (1000T)	25	250	10.0	16288.0	15777.8	9099.3	9587.0
	50	250	5.0	13136.7	12954.5	9437.9	10538.3
	100	250	2.5	10868.4	10824.3	10865.3	8543.4
BC4 (100T)	25	250	10.0	1890.0	1975.3	857.1	842.0
	50	250	5.0	1434.2	1436.3	876.5	685.9
	100	250	2.5	1185.6	1218.7	1104.3	412.8
	75	100	1.3	2258.1	2121.8	1597.7	1352.1
	100	100	1.0	2330.0	2177.4	1599.2	1096.6

Table 21: Total line costs for comparable case studies.

				Total line cost [M£]			
Device	**Water depth [m]**	**Footprint [m]**	**Footprint – depth ratio**	**Chain G3**	**Chain G4**	**EA/BL 8**	**EA/BL 4**
BC2 (1000T)	25	250	10.0	0.69	0.50	0.17	0.18
	50	250	5.0	0.60	0.36	0.18	0.20
	100	250	2.5	0.54	0.30	0.21	0.17
BC4 (100T)	25	250	10.0	0.09	0.06	0.03	0.02
	50	250	5.0	0.07	0.06	0.03	0.02
	100	250	2.5	0.07	0.03	0.04	0.02
	75	100	1.3	0.05	0.06	0.02	0.02
	100	100	1.0	0.06	0.06	0.03	0.02

For all of the cases studied in this section the total line costs of the synthetic rope systems are lower than the chain systems (Table 21). These results highlight that at low footprint-water depth ratios the maximum horizontal excursions of the device are comparable for both synthetic rope and chain mooring systems. Therefore lower cost mooring systems are possible with synthetic rope lines with the added benefit of lower line tensions (and hence loads transferred to the anchors and device hull). Furthermore these advantages are also applicable if larger horizontal device excursions can be tolerated.

Some WECs have a power export cable attached and therefore excursion limits are important. In this case it may be possible to use different (design) extreme conditions for the mooring system and cable if a quick and/or partial release connection is used that can be disconnected in the most extreme conditions. This highlights the need for robust and reliable quick release systems that can be easily reconnected either manually or automatically following a storm. Note: it is likely that many systems will not be producing power and will be in shutdown mode for the extreme wave which would relate to the maximum excursions.

Conversely other WEC designs may not require a permanent electrical connection between the device and grid. Alternative approaches have been proposed, such as chemical storage (e.g. [118]).

For large excursions associated with very compliant moorings the conventional umbilical design approach and state-of-the-art technology may not always be practical. This reinforces the contradiction that WEC developers want low mooring line and anchor loads, but also low mooring system compliance for power export. Therefore a priority in terms of making a step change in cost of energy is to reduce the mooring and anchor loads and then look at innovative ways of exporting the power for mooring system with large excursions (in all modes of motion).

6.4 Foundation Requirements

The following plots compare the total required gravity mass in air and total foundation costs for both chain- and nylon-based mooring systems. The example chosen was for the 1000T BC2 buoy with a mooring footprint of 1000m and water depth of 100m. For the purposes of this comparison Grade 3 chain and the higher storm stiffness of nylon were chosen (EA/BL=8). Trends for other cases are also commented on briefly.

6.4.1 Comparison of Foundation Weight with Type

In terms of total foundation weight (for all four mooring lines). Figure 87 demonstrates a significant benefit of drag embedment and vertical lift plate-type anchors (DEAs and VLAs) compared to the gravity base anchors. The plot also highlights the impact on mooring compliance on required foundation mass. In this example the chain-based mooring required a total GBA mass in air of 8064T, this figure reduces to 932T for a nylon-based mooring which is almost equal to an order of magnitude weight saving. Assuming the existence of suitable sediment for a DEA (e.g. stable sediment ~6m deep), the mass of anchors for a chain-based system reduces from 8064T for a gravity mass to 40T for a DEA and similarly from 932T to 6T for these anchors used with a nylon-based mooring system. A VLA would normally be considered when there is vertical uplift at the anchor greater than 10 degrees and would be more suited to a semi-taut synthetic mooring. The use of VLAs with a chain-based system was not considered as the angle of uplift is typically less than 10 degrees and DEAs are considered easier to install and offer wider suitability with respect to different seabed types. When considering the data for smaller footprints (not shown) the benefit of nylon-based mooring is less substantial but still significant. For example for a mooring footprint of 500m the total GBA mass (averaged across all water depths) for chain-based moorings is 13667T compared to 8975T for nylon-based moorings. For the 5000T BC1 buoy the required GBA masses identified are deemed to be very excessive with a peak GBA mass of 23586T calculated.

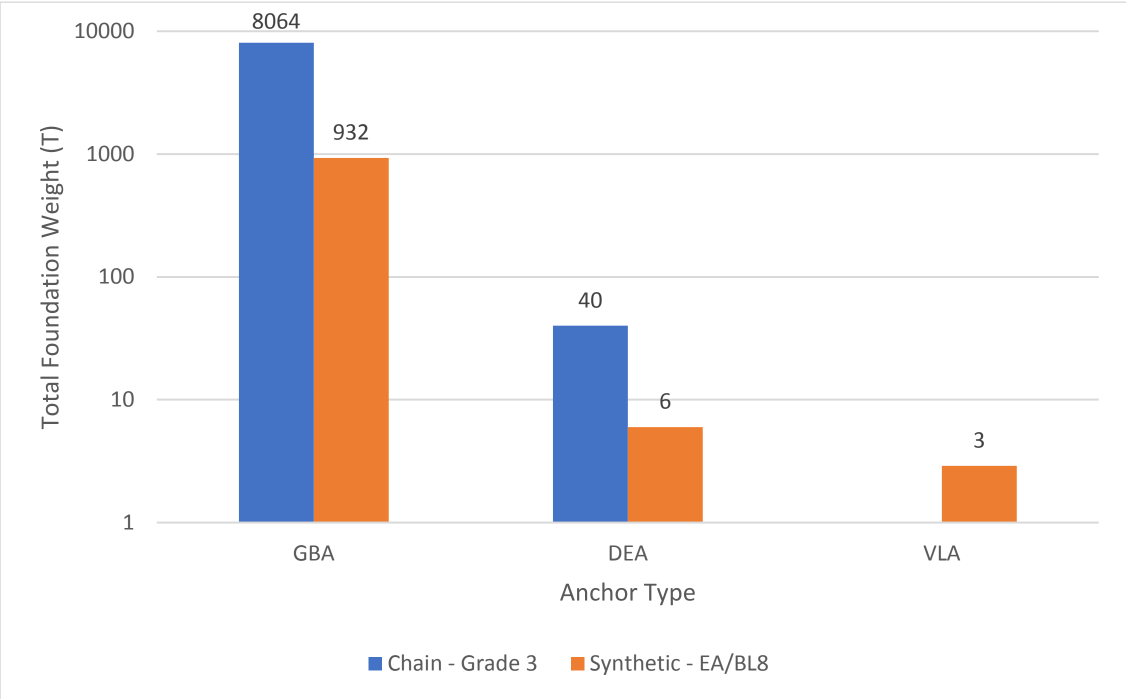


Figure 87: Total foundation weight requirements for BC2 (1000T), 1000m mooring footprint and 100m water depth for both chain (Grade 3) and nylon (EA/BL=8) based moorings (logarithmic scale).

While the synthetic rope-based system results in significantly lower line tensions and hence anchoring requirements, there will be a compromise. For larger footprints the combined affect of lower axial line stiffness and footprint size will lead to a high mooring system compliance which could result in potentially large and undesirable WEC excursions. To reduce excursions a higher mooring system stiffness would be required which would then result in higher anchor loads and associated foundation costs. The 1000m footprint has been chosen to illustrate the impact on foundation costs, alternatively it may be possible to generate similar compliance using combined synthetics and shock absorbers. Based on TTI's experience a footprint of 1km radius is broadly in line with what some large-scale wave device and floating offshore wind turbines require on exposed coasts.

6.4.2 Comparison of Foundation Cost with Type

CAPEX costs (shown in Figure 88), which omit installation costs, can be calculated directly from foundation weights (shown in Figure 87). The calculated costs are based on the assumptions that: i) GBAs are made up of modular concrete blocks with a manufactured cost of £742 per tonne and ii) DEAs and VLAs are steel with a manufactured cost of £5000 per tonne. From Figure 88 it can be seen that the total cost to manufacture concrete GBA is £5.25M for chain-based mooring and ~£600K for nylon-based mooring. Whereas for a steel DEA the costs are £200K and £30K for chain and nylon-based respectively. VLA for synthetic based mooring is estimated to be about half the cost of the DEA at ~£10K due to the higher effective holding capacity. The costs for GBA for the BC1 5000T are excessive and are of the order of £12-15M.

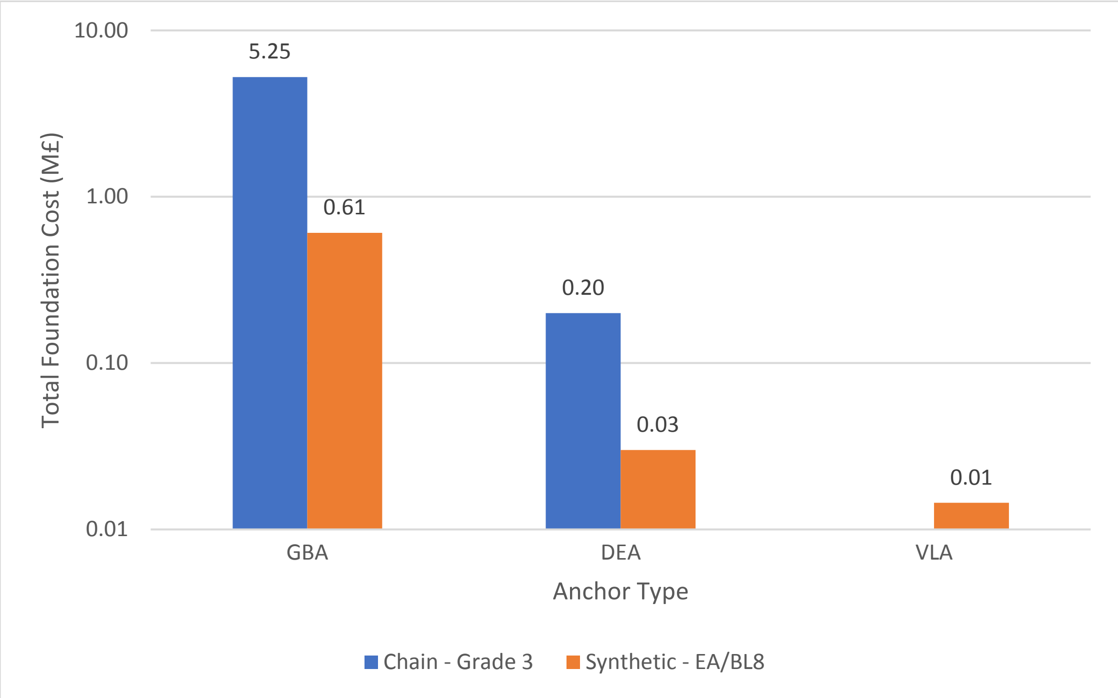


Figure 88: Total foundation cost for BC2 (1000T), 1000m mooring footprint and 100m water depth for both chain (Grade 3) and nylon (EA/BL=8) based moorings (logarithmic scale).

To provide insight into the relative holding capacities of GBAs and DEAs, Table 22 presents the unitary holding capacity of anchors based on a factor of safety of 1.5 and (for the GBA) a seabed coefficient of friction of 0.5. The values for the DEAs originate from the Vryhof catalog [40] and are based on the ultimate holding capacity of the Stevpris Mk6 anchor. The GBA values are based on a force vector calculation. While the ultimate holding capacity of a DEA is always multiple time higher than the actual anchor mass, the holding capacity of the GBA is significantly lower than the anchor mass, even when the whole anchor mass is used to take up line tension vertically (due to the factor of safety that must be applied). However, a DEA can only be used in sedimentary seabed of sufficient depth and has limited scope for vertical loading (see Section 6.4.3). Conversely a GBA can accept any angle of pulling and is much less dependent on the seabed characteristics.

Table 22: Comparative performance of GBAs and DEAs. A factor of safety of 1.5 has been assumed.

Anchor and soil type	Wet mass (T)	Ultimate Holding Capacity at 15° pull angle (T)	Ultimate Holding Capacity at 90° pull angle (T)
GBA	1.0	0.3	0.66
DEA in very soft clay (mud)		35.0	N/A
DEA in medium clay		47.0	
DEA in sand and hard clay		63.0	

6.4.3 Impact of Mooring Footprint, Water Depth & Site on Foundation Selection

GBAs can be used on any seabed but conventional GBA's can be prohibitively expensive and hence tend to be favoured for mooring systems featuring significant vertical loading. If suitable seabed condition exists well-selected DEAs tend to be comparatively more cost-effective but do have a number of limitations. Smaller mooring footprints and deeper water depths results in higher uplift angles at the anchor, making the DEA less feasible. Design guidance suggests that the uplift at the DEA should not be greater than 10 degrees [119], although there is some evidence that DEAs, when deployed in suitable conditions, can resist vertical loads of upwards of 20 degrees [40]. For reference Figure 89 shows the approximate trigonometric relationship of uplift angle to mooring footprint for a range of water depths, calculated as$uplift\ angle = \tan^{-1}\left(\frac{water\ depth}{footprint}\right)$. Based on a DEA limit of 10 degrees this plot demonstrates that minimum allowable mooring footprints are 142m and 567m for respective water depths of 25m and 100m. However, DEA feasibility is very site specific and on a typically exposed commercial scale site sufficient sediment cover can be scarce or possibly be migratory and cannot be relied upon. If the uplift angle of the DEA is exceeded then plate, VLA is a cost-effective alternative but would tend to be more suitable for deeper water depths, and has a requirement for deeper stable sediment.

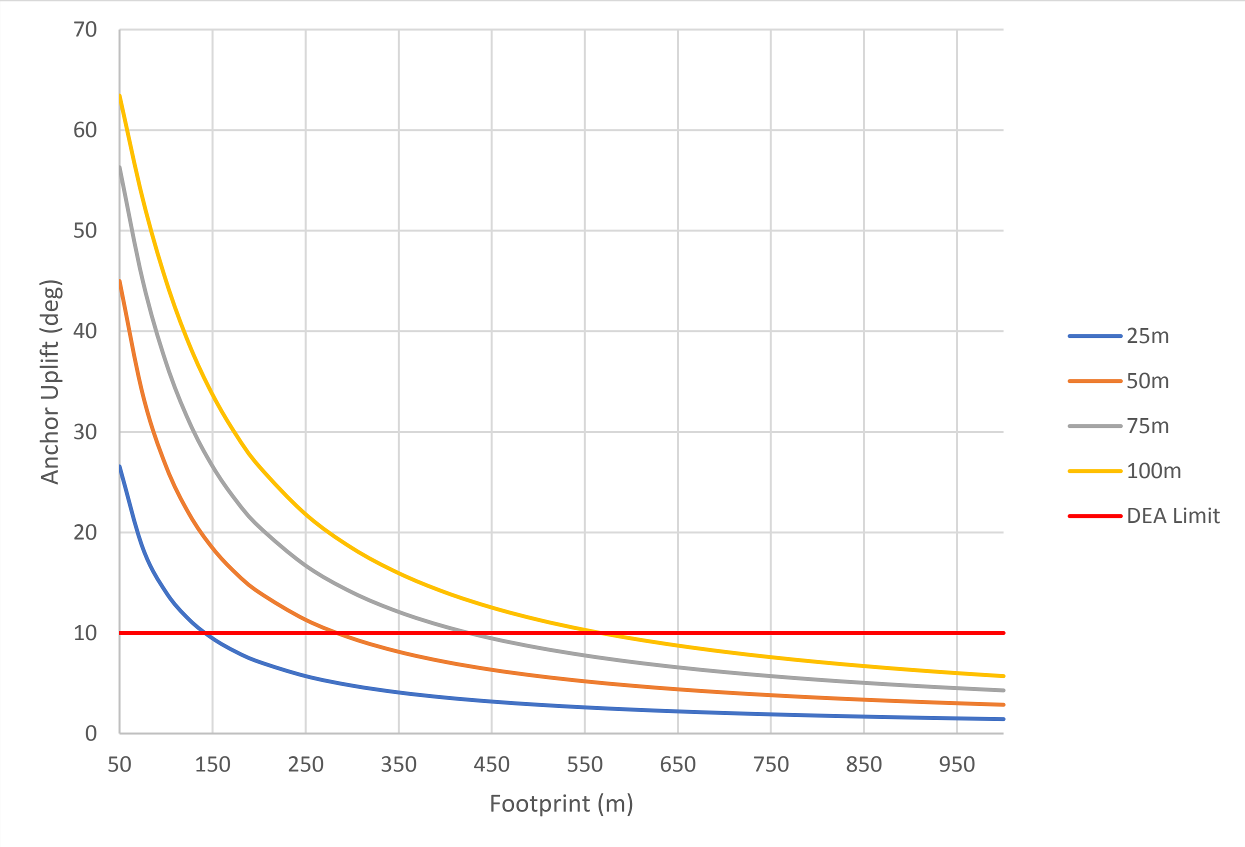


Figure 89: Line uplift angle at anchor for a range of footprints and water depths (source: TTI).

Rock anchoring, piling, suction and hybrid solutions have not been considered within this scenario-based study. However, this study provides an economic benchmark for alternative foundation solutions. Rock anchoring and rock piling are very site-specific and depend on how consolidated the substrate is and the extent of sediment layering on top of the substrate (overburden). For piling in sediment similar to fixed offshore wind monopiles, the availability of suitable sediment is less likely unless deep muds are available, where pile/suction bucket technology could become attractive. The economic impact of being further offshore would need to be fully understood as this has a direct influence on export cable length and site accessibility.

The seabed conditions and uplift angles can vary over the footprint of the mooring and array and as a result a mix of foundation technology solutions may be required. Sections 6.4.1 and 6.4.2 have highlighted that gravity-based anchoring can be prohibitively expensive, particularly for the larger scale devices and chain-based mooring. However, it has been demonstrated that with sufficient mooring compliance the requirement on gravity anchoring can be significantly reduced to more manageable levels. The compromise of providing compliance is increased device excursion and also mooring footprint. It may be possible to reduce the required mooring footprint by providing compliance by other means (e.g. a combined shock-absorber, synthetic system). As identified by the mooring landscape and TRIZ innovation exercise there are opportunities in particular to develop gravity-base and semi-autonomous rock anchoring technologies – which could be used across a range of site conditions. As previously mentioned drag embedment anchors are highly efficient and any future improvements are likely to be marginal. It may be that the sector, when deploying first of a kind or early arrays, should adopt a risk-averse approach and target sites with suitable sediment for DEA.

6.5 Impact of Foundation Type on Installation Cost

Estimated installation costs (averaged for all water depths and mooring footprints) for the three device scales are shown in Figure 90 to Figure 92 based on the assumptions introduced in Section 6.2.6. Though the costs vary, the general trend of foundation costs is similar for the three device scales moored with synthetic ropes, with foundation costs increasing alongside the scale of the technology. However, it should be noted that the installation cost per tonne of device mass does decrease significantly. On the other hand, the chain cases only show a similar trend for BC4 and BC2. For BC4, the average cost of installation is comparable with the BC4 synthetic rope cases; however, for the larger BC2 case, the difference in average cost between the chain and synthetic rope cases are much more significant. The BC1 chain cases appear to show much lower costs and do not follow the trend of the BC2 and BC4 device scales, particularly the gravity anchor costs. The reasons for this are two-fold: i) due to the lower level of successfully identified mooring systems in the BC1 case (see Section 6.2.5) the costs are averaged over a small set of comparable cases; four synthetic rope cases and two chain cases[36] and ii) the installation costs are driven by crane lifting capacity and transportation capacity, however the crane lifting capacity is not always proportional to vessel charter costs. Therefore it is expected that if more cases were available then a similar trend as for the BC2 device scale would have been observed.

[36] The installation cost for one synthetic rope case was relatively high compared to the other three which pushed up the average.

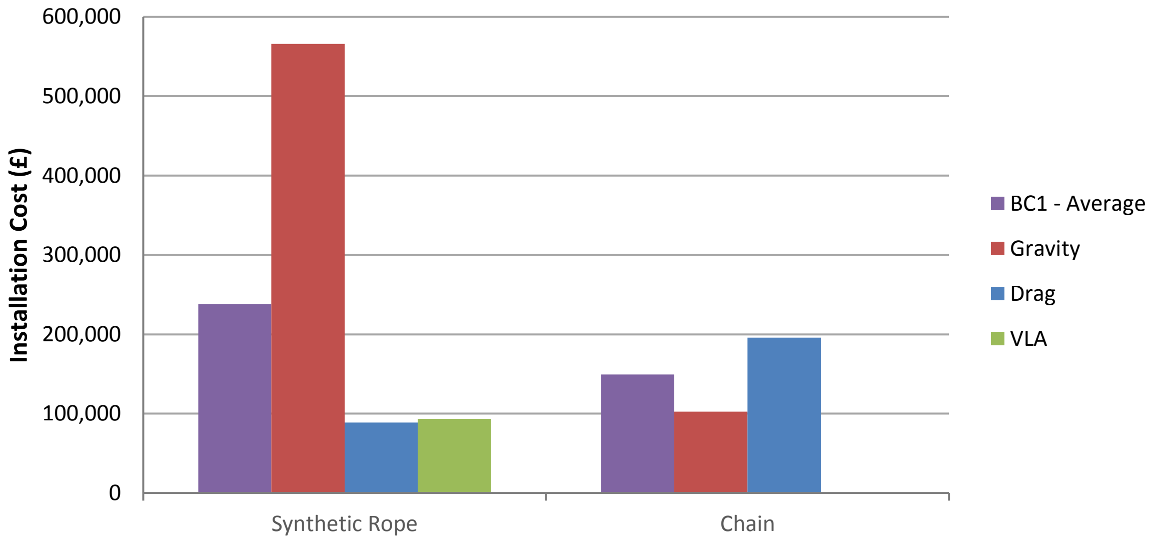


Figure 90: Estimated installation costs based on anchor type for device BC1 (5000T). Installation costs are for the combined cost of lines and anchors and are averaged over all analysed cases.

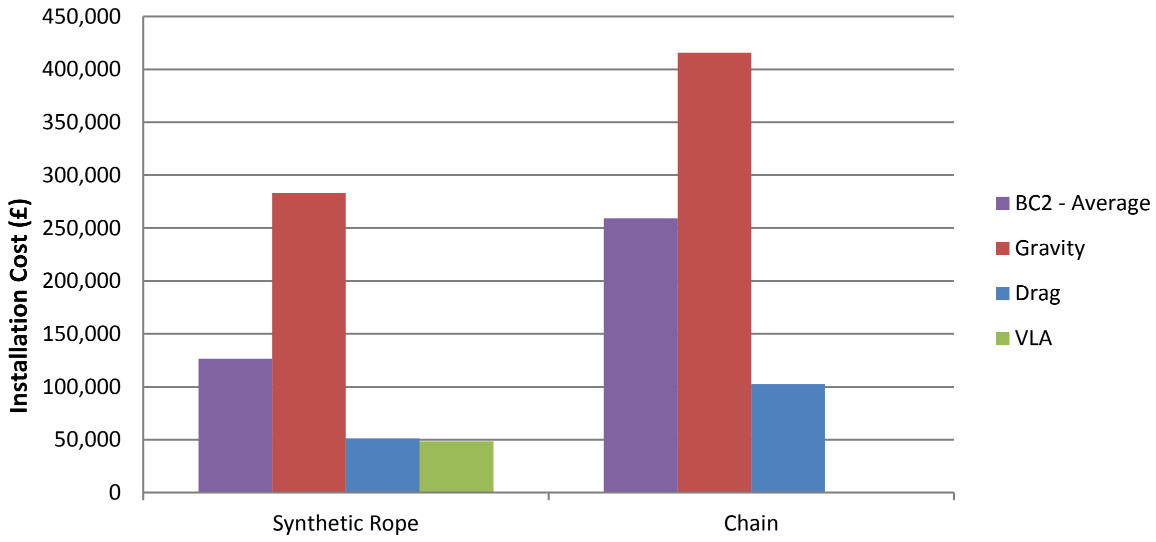


Figure 91: Estimated installation costs based on anchor type for device BC2 (1000T). Installation costs are for the combined cost of lines and anchors and are averaged over all analysed cases.

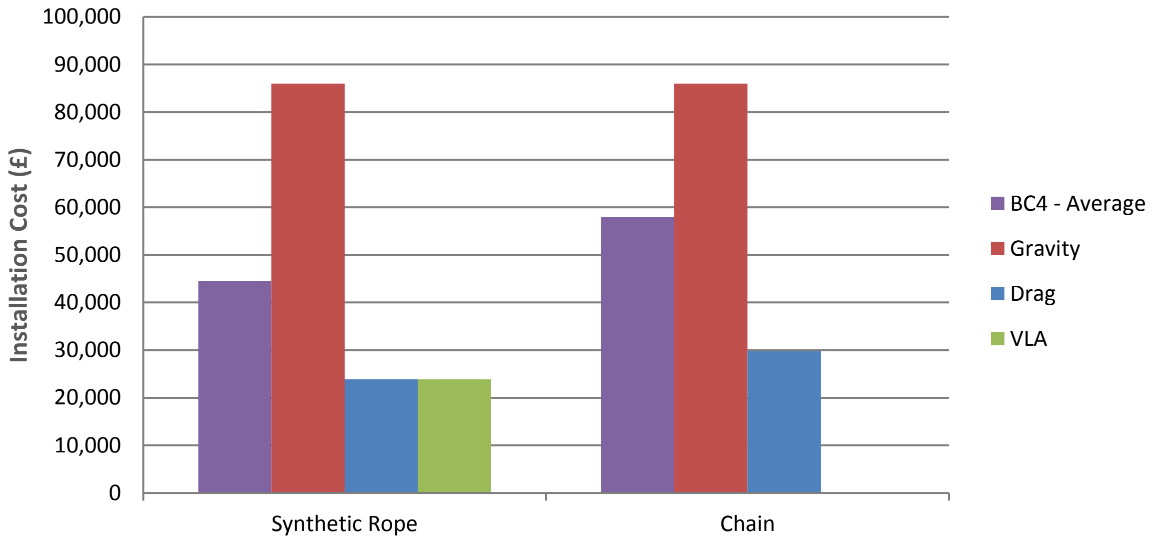


Figure 92: Estimated installation costs based on anchor type for device BC4 (100T). Installation costs are for the combined cost of lines and anchors and are averaged over all analysed cases.

6.6 Impact on Levelised Cost of Energy

An LCOE analysis was completed by Black & Veatch (B&V) as part of an assessment of the financial impact of mooring system design choices on the overall cost of WEC projects. Multiple influencing factors were considered; including the cost per tonne of steel, average generation (kW) capacity per tonne (of WEC device mass), failure rates (of the mooring and foundation components), and the capacity factor of the wave energy technology. In total, 89 cases from the previously obtained results were analysed and trends within the data sought to establish the impact of the aforementioned parameters on the LCOE of wave energy projects.

6.6.1 Analysis Assumptions and Calculation Procedure

The following constant and variable parameters are assumed:

Constant Parameters

a) A project lifetime of 20 years.
b) For the NPV calculations, an interest rate of 5% has been used. Although this is low for the current status of the sector, its influence on the comparative results is low (as the influence of OPEX in comparison to CAPEX is low).
c) The cost of replacement parts is set at 50% of the CAPEX of moorings (if a failure occurs during the lifetime). This has been set with the purpose of having a CAPEX replacement when a mooring fails. This is case specific but 50% of the CAPEX is a reasonable assumption as some parts of the system may be reused (note that, in fact, failures rarely occur).
d) The levelised total costs used were based on the findings of the IEA OES report ([120], see Figure 93), which states the following cost share of the following components for wave energy technology at the current state of development:
    - Structure & Prime Mover, 30% (this value was taken as the mass of each device scale multiplied by the assumed cost of steel per tonne and then used as 30% of the total. It is therefore assumed that no lower cost ballast material is used)

- Power Take-Off (PTO), 20%
- Electrical Connection, 5%
- Mooring system including anchors, 10% (this was replaced with the CAPEX results presented above)
- Installation, 10%
- Operations & Maintenance, 25% (the analysis accounted for the probability of device/part failure by using the calculated MTTF. If the device/part fails within the project lifetime (20 years), a repair cost (based on the author's experience) is added to this 25% of total costs. It should be noted that due to the MTTF values, failures generally do not occur during the lifetime and only in very few cases in the sensitivity analysis do failures actually occur).

e) The mooring and foundation CAPEX (presented above). These costs included an assumption of installation costs for the moorings cost centre (vessel day rate multiplied by the number of installation days, see Section 6.2.6), the value for which was then subtracted from the 10% IEA OES report assumption for installation, so as to avoid double accounting.

f) Threshold costs for the current state of the sector and future targets for commercial readiness were taken from [120].

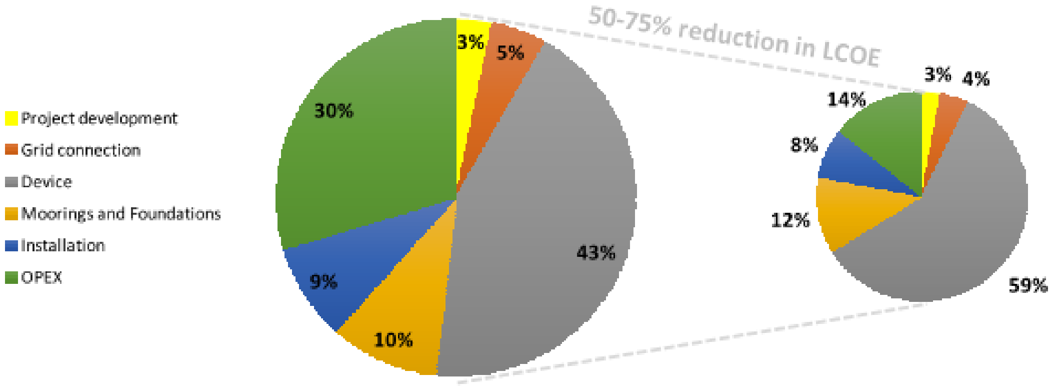


Figure 93: Wave LCOE percentage breakdown by cost centre values at current stage of development (Left) and the commercial target (right). Reproduced from [120].

Variable Parameters

Some of the input parameters carry significant uncertainty, and therefore a Monte Carlo analysis was undertaken in order to determine the impact of the uncertainty on the outputs:

a) Some parameters were given a distribution using the @Risk software developed by Palisade, using 10,000 iterations to provide a Monte Carlo risk analysis.

b) The electrical capacity to structural displacement mass ratio has a central value of 0.75 tonne/kW. This parameter was given a triangular distribution, between 0.5 tonne/kW and 3 tonne/kW. Use of triangular distributions allowed for plausible minimum, maximum and most likely values for each input.

c) The wave energy technology capacity factor has a central value of 25%. This parameter was given a triangular distribution between 15% and 60%.

d) The cost of steel has a central value of £4,700/tonne. This parameter was given a triangular distribution between £3,000/tonne and £6,000/tonne.

e) The exchange rate has a central value of 1.14€/£. This parameter was given a triangular distribution between 0.912€/£ and 1.482€/£.
f) The MTTF parameter was given a triangular distribution between 0.1 and x10.

The aforementioned assumptions in the LCOE analysis have associated uncertainties. To acknowledge these Table 23 lists the potential impacts of these uncertainties and recommendations for addressing them in future analyses.

Table 23: Uncertainties in the LCOE analysis and potential impacts in the context of MRE M&F systems.

Uncertainty	Error(s)	Impact(s)	Recommendation(s)
The use of performance data for devices different from those modelled in this study, including capacity factors and rated power to structural displacement mass ratios.	The performance metrics used may not be representative of devices currently being considered.	Performance may be under- or over-estimated in cost modelling.	Developer to apply relevant performance metric when conducting their own analysis.
The assumption that device energy capture is unmodified by alteration of the mooring.	The choice of mooring setup can significantly influence the level of power captured by the device.	Performance may be under- or over-estimated in cost modelling.	Analyses should be conducted to ascertain the influence of the mooring system on device performance for an adequate range of operating conditions.
The cost of replacement components is set at 50% of the component CAPEX.	The replacement cost will depend on the component, availability and period of time (i.e. inflation).	Under- or over-estimation of OPEX.	Replacement costs to be identified for all components and subsystems taking into account any impact of inflation.
Other cost centres are unaffected by the choices made in M&F system design.	The choice of mooring setup can influence the design of other subsystems.	May lower or increase the other cost centres.	Cost analyses to be carried out on the whole system in question and any interrelations accounted for.
The LCOE thresholds are unchanged since the IEA OES report was published (2016).	Threshold targets may have altered since 2016.	Requirements for the M&F cost centre may be less severe or more onerous.	In the absence of more up-to-date targets, use values in the IEA OES report.
The WEC hull structure is fabricated exclusively	Assuming devices are constructed entirely from steel without	Device cost centre excessively high for some devices.	Developer to apply actuals costs of fabricated structure.

Uncertainty	Error(s)	Impact(s)	Recommendation(s)
from steel with a central value of £4,700/tonne.	any lower cost ballast is not realistic for some device designs.		
The component failure rates used are applicable to WEC M&F systems.	The failure modes (and hence failure rates) are based on offshore petroleum platforms and might not be applicable to WEC M&F systems.	Mean time to failure metrics may be under- or over-conservative.	An initiative is required to share failure rate data across the WEC sector.

TOTAL LCOE CALCULATION

For each case, the total LCOE (including all cost centres and the aforementioned CAPEX) was extrapolated using the IEA OES report [120]. For example, if the Structure & Prime Mover cost £300,000 (30%), the PTO would cost £200,000 (20%), Electrical Connection would cost £50,000 (5%), the installation would cost £100,000 (10%), and the operations and maintenance would cost £250,000 (25%, in addition to any repairs that occur based on the calculated mooring and foundation MTTF and assumed repair costs). The one exception to this was the mooring and foundation cost centre (which according to [120] is 10% but the calculated CAPEX was used instead).

This total LCOE was determined using an NPV calculation. The annual energy production was based on the mass of each case, using the assumptions for the electrical capacity to displacement mass ratio and the capacity factor.

6.6.2 RESULTS

MOORING AND FOUNDATION COST CENTRE

Figure 94 presents the relative comparison of LCOE between the synthetic rope and catenary chain cases at varying water depths using the following percentage:

$$LCOE_{Ratio} = 100 * \frac{LCOE_{SR}}{LCOE_C} \quad (4)$$

Where $LCOE_{SR}$ and $LCOE_C$ are the LCOE values for comparable synthetic rope and chain cases respectively.

As stated in Section 6.6.1 these results are based on an assumed installation cost centre (10% of the project LCOE), which is common for all scenarios. In Sections 6.3.4, 6.4.1, 6.4.2 and 6.5 it has been demonstrated that there are considerable cost and weight savings to be had by adopting synthetic rope systems. This is likely to be reflected in the installation LCOE cost centre and this is worthy of further R&D effort as the WEC sector matures.

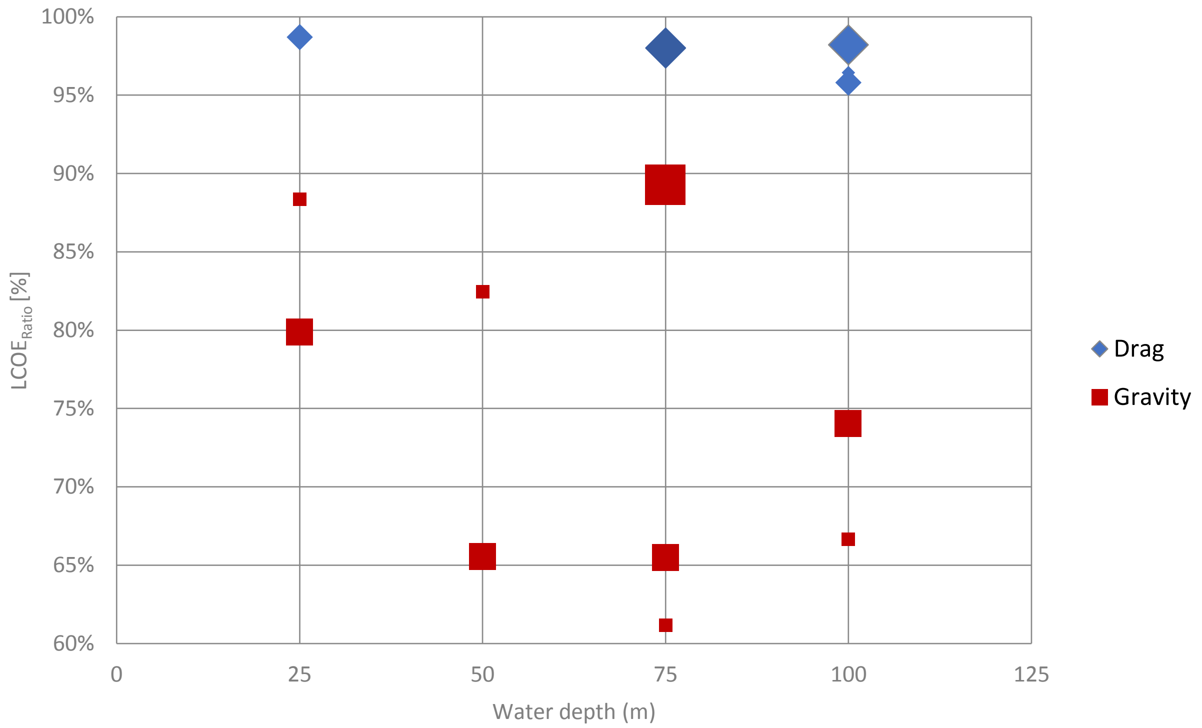


Figure 94: Ratio of LCOE values for comparable synthetic rope and chain cases at varying water depths for drag and gravity anchors. Marker size relates to device scale: BC4 (small), BC2 (medium) and BC1 (large).

In all cases, the LCOE of the synthetic rope cases are shown to be less than the equivalent LCOE of the catenary chain cases, demonstrating the potential for cost reduction by selecting synthetic mooring components. A comparison was only conducted if there was a case with matching designation, anchor type, footprint and water depth for both chain and synthetic rope systems. It should be noted that there were a small number of comparable cases for the largest device scale (BC1). In general the gravity anchor cases demonstrate greater relative savings than the drag anchors and this is due to the influence of line tensions on the associated holding capacity requirements of the larger, bulky anchors. For the BC2 and BC4 device scales there appears to be a trend of increasing cost savings (by adopting a taut synthetic system) with water depths up to 75m depth. For the deepest water depth studied, the cost savings are reduced, although more data points are probably required before firm conclusions can be drawn.

The calculated percentages listed in Table 24 illustrate that while the traditionally assumed 10% for the mooring and foundation cost centre [120] falls within the bounds of the results, the minimum and maximum values cover a large range. In general, the chain catenary cases are shown to represent a comparatively high proportion of total levelised costs in comparison to the synthetic rope cases, with maximum percentages reaching ~49% for chain and ~39% for synthetic rope. The calculated mean values for the synthetic cases are all under the assumed 10% level. With both types of line, the mean percentage of total costs that the mooring and foundation system represents increases as the device scale decreases. It is also noted that for all but one maximum value listed in Table 24 corresponds to devices with large mooring footprints in shallow water; which is generally a particularly challenging scenario which is reflected by the resulting costly solutions. All maximum values also suggest that gravity foundations are themselves costly and if appropriate other foundation or anchor solutions may be more cost-effective. Although these LCOE figures have been computed with significant assumptions on the other cost centres, the results are expected to be representative in relative terms. The figures presented highlight the importance of the mooring cost centre and the importance of achieving cost reductions within this cost centre to achieve lower LCOE.

Table 24: Percentage breakdown of mooring and foundation cost centre relative to the total LCOE. Corresponding case parameters are indicated in parenthesis for reference (water depth, mooring footprint radius, anchor type).

Device	Chain (%LCOE)			Synthetic Rope (%LCOE)		
	Min	Mean	Max	Min	Mean	Max
BC1	2.56 *(100m, 1000m, Drag)*	8.03	14.94 *(75m, 1000m, Gravity)*	0.39 *(100m, 1000m, VLA)*	2.65	13.84 *(25m, 1000m, Gravity)*
BC2	5.86 *(100m, 1000m, Drag)*	22.63	45.22 *(25m, 1000m, Gravity)*	0.52 *(75m, 500m, VLA)*	4.73	39.09 *(25m, 1000m, Gravity)*
BC4	8.65 *(75m, 250m, Drag)*	26.66	48.59 *(25m, 1000m, Gravity)*	3.81 *(25m, 100m, VLA)*	9.81	33.63 *(25m, 1000m, Gravity)*
All	2.56 *(100m, 1000m, Drag)*	21.32	48.59 *(25m, 1000m, Gravity)*	0.39 *(100m, 1000m, VLA)*	5.86	39.09 *(25m, 1000m, Gravity)*

To assess the results against the current state of the sector, the results were matched against target or threshold values for total project CAPEX, as provided by [120]. The threshold levels for current development range between (£3,250 - £14,706 (£/kW)) with commercial targets ranging between (£2,194 - £7,394 (£/kW)). The upper and lower bounds of these values correspond to deployed projects ranging from 1-3MW. Expressed in terms of CAPEX per kW of device rating it can be seen in Table 25 that the range of calculated CAPEX/kW includes minimum values that are below the current and commercial deployment targets and these all correspond to synthetic rope cases. Conversely, the maximum CAPEX/kW values all correspond to chain cases, with only one (the BC1 device scale) within the current or commercial development target ranges. Considering all of the synthetic rope and chain scenarios where a solution was found, the mean values are within or below the threshold ranges indicating that, with the exception of unfeasible, prohibitively expensive solutions, most fit within the levels required for the commercial development of wave energy devices. It should, therefore, be a priority to focus on the currently expensive and/or difficult scenarios (i.e. large devices in shallow water depths) in order to allow widespread deployment of this technology.

Table 25: Ranges of calculated CAPEX per kW. Corresponding case parameters are indicated in parenthesis for reference (system type, water depth, mooring footprint radius, anchor type).

Device	Mooring and foundation system CAPEX (£/kW)		
	Min	Mean	Max
BC1	71.25	709.78	3273.86

	(Synthetic rope, 100m, 1000m, VLA)		*(Chain, 75m, 1000m, Gravity)*
BC2	92.98	2374.77	13812.20
	(Synthetic rope, 50m, 500m, VLA)		*(Chain, 25m, 1000m, Gravity)*
BC4	684.93	3473.97	16375.15
	(Synthetic rope, 25m, 100m, VLA)		*(Chain, 25m, 1000m, Gravity)*
All	71.25	2302.29	16375.15
	(Synthetic rope, 100m, 1000m, VLA)		*(Chain, 25m, 1000m, Gravity)*

Pathways to Reducing Installation Costs

The International Energy Agency (IEA) Ocean Energy Systems (OES) *International LCOE for Ocean Energy Technologies* report [120] states that the total installation costs currently represent 9% of the overall project LCOE therefore reductions for this cost centre are essential to allow MRE projects to become financially viable [121]. Factors affecting installation cost are addressed in Section 6.2.6. One of the key elements to be considered in the cost assessment of such marine operations is the availability of suitable high capacity installation vessels, such as tugs, supply vessels or crane vessels able to perform marine operations even in harsh weather. As illustrated in Figure 95, charter costs are highly variable and usually dependent on season and vessel availability. Concerns over high installation costs were echoed in the VOC survey reported in Section 4.

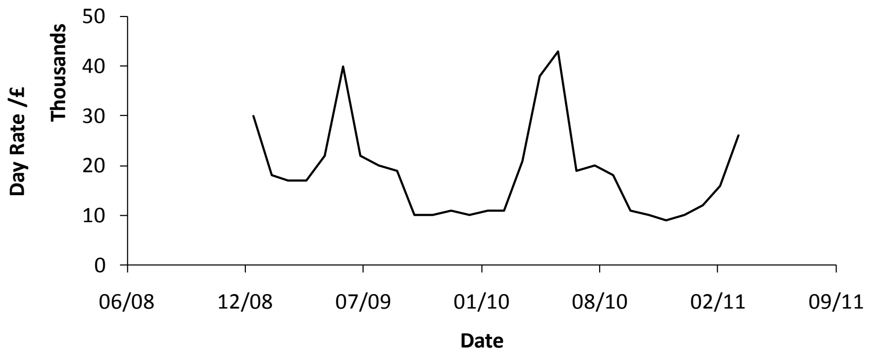


Figure 95: Example day rates for an anchor handling tug (December 2008 to April 2011). Reproduced from [122].

While the installation procedures required for a specific WEC mooring and foundation system is likely to be design dependent, several general pathways to reducing installation costs are listed in Table 26. Some of these pathways have already been demonstrated or are currently in development and already many of these are technical in nature, a significant contribution can be made from efficient logistical measures, including the accurate prediction of weather windows that are suitable for installation operations. For example Mermaid® is a software package developed by Mojo Maritime[37] which allows marine operations to be planned and risk analysis to be conducted, based on user-supplied metocean and vessel data, as well as the geographic location of the site and nearby ports.

[37] Mermaid®' [Online] http://mojomermaid.com/ [Accessed: 05/03/2018]

Table 26: Potential cost reduction pathways for WEC device (or array) mooring and foundation installation

Technical	Logistical
• Innovation (design for installation and maintenance) • Specialist vessels which can operate in adverse weather and site conditions (i.e. high current velocity sites) • Shared foundation, structure or moorings to reduce installation times (lower deployment costs per MW) • Remote or autonomous commissioning • Use of vessel tracking to track transit progress and to inform future deployments	• Utilisation of local port facilities, expertise and vessels • Efficient supply chain liaison to avoid bottlenecks • Utilise experience of the offshore wind industry • Use of state-of-the-art weather window planning tools which can simulate several installation scenarios and utilise accurate weather data, vessel charter costs and capabilities

SENSITIVITY ANALYSIS

In order to determine the influence of independent variables on the dependent variables, LCOE sensitivity analysis was conducted based on the assumptions outlined in Section 6.6.1. Figure 96 provides an example of the analysis which revealed that the independent variable with the largest effect was the ratio between the device tonnage and electrical capacity, followed by the capacity factor and the cost of steel. In this figure the LCOE baseline (100%) represents the central values of the variable parameters listed in Section 6.6.1. It should be noted that the cost of steel only affected the structure and prime mover cost centre and not the mooring lines (although it is acknowledged that fluctuations in steel cost are likely to affect chain and connecting hardware costs[38]). The number of failures had a smaller than expected impact, despite being varied up to ten times the designated value. This was most likely due to the large MTTF, which was substantially longer than the prescribed project lifetime. For example, the MTTF ranged from 244 years to 5,035, which are orders of magnitude larger than the proposed 20-year lifespan. It is acknowledged that this is potentially unrealistic; however, it is based on limited mooring and foundation failure rate data in the public domain (see Section 3.3.4) which was modified to take into account the typical number of lines on offshore O&G production equipment[39]. To account for this, a high level of uncertainty was included (from 0.1 to 10 times more likely to fail); however, the impact of this was still minimal due to the initial input figures. These results are partly due to the calculation method, with the overall CAPEX being

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[38] The authors are not aware of a long-term record of steel component prices in the public domain. However costs are intrinsically linked to the variability of the raw material (iron ore) bulk price. Wårell, L. in [128] reported high variability of iron ore prices, ranging from approximately 30-180 US$ per tonne between 2003 - 2017.

[39] Accounting for the number of lines in the estimation of failure rates was necessary because a high level of redundancy is built into O&G mooring systems. A key issue is that a failure is often reported as a single event, with often no information provided on the number of lines which have failed, the type of component(s) or indeed failure mode(s). Therefore the actual number of failures in O&G equipment is likely to be a lot higher than what has been used in this study.

based primarily on the cost of steel assumption and the device tonnage, which would have a significant effect on the final LCOE. Similar results were obtained for all of the other cases studied.

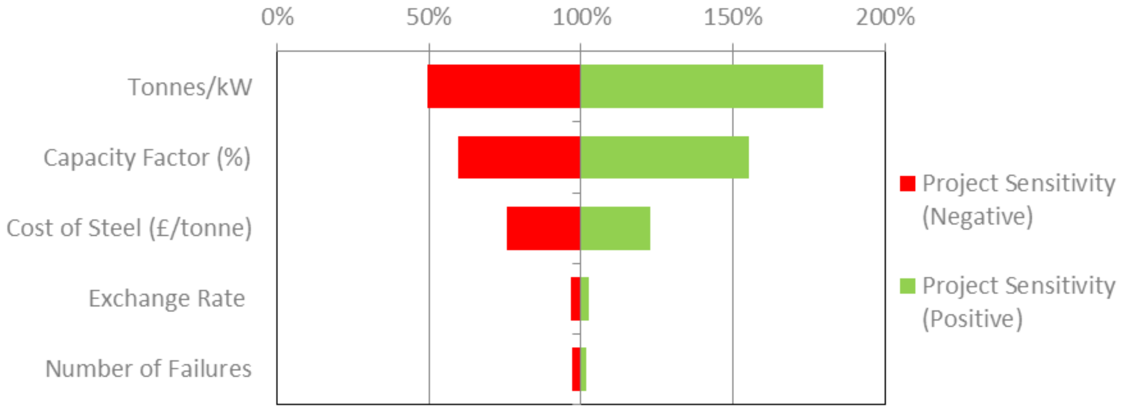

Figure 96: Example of LCOE sensitivity analysis, run 1 of 89 (chain). Note: 100% represents the LCOE baseline calculated using the central values of the variable parameters.

7 CONCLUSIONS AND OPPORTUNITIES FOR COST REDUCTION, INNOVATION AND FUTURE R&D

7.1 CONCLUSIONS

The purpose of this report has been to present findings on a Landscaping Study focused on mooring and foundation systems for wave energy converters. The four different strands of work considered have provided a range of interrelated perspectives, combining a review of the state-of-the-art, a survey of the industrial sector, an exercise in innovation identification (using the TRIZ approach) and also a quantitative study on the influence of mooring system compliance and foundation selection for several generic scenarios. Main conclusions from each of the four work strands are summarised below:

7.1.1 STATE-OF-THE-ART

Due to the challenging nature of wave energy sites and diversity of wave technology and mooring categories being considered it is clear that other marine sector solutions are not always directly transferable or sufficiently reliable, viable or affordable. These challenges provide the motivation to develop and test alternative forms of mooring compliance and novel anchoring systems that are not only cost effective themselves but also allow more economical methods for installation, maintenance and decommissioning. The review also considered the relevance of current mooring analysis methodologies, design codes and the need for condition monitoring protocols. One key aspect is the acceptance of novel materials and designs by classification societies. The example of the qualification of nylon ropes for floating wind turbine mooring systems was provided in Section 3.3.3, including the outstanding challenges which remain at the time of writing, such as the development of suitable testing procedures. Furthermore due to the fact that mooring line properties can have a direct impact on device motions (and hence the level of power capture) it is essential that methods are developed to adequately represent these materials in system analyses.

7.1.2 VOICE OF THE CUSTOMER (VOC)

The range of devices for which responses were submitted is broad as is the range of site conditions, which is representative of the sector. Intended mooring systems are also broad-ranging and it is clear that the sector appreciates that there is no “one-size-fits-all” type solution: the mooring system design is intrinsically coupled to the WEC design and development and the environmental conditions at the deployment site. Some developers appreciate that this requires engaging with the specialist supply-chain at early stages in the WEC design process, but not all. A high percentage (60%) of respondents seek compliant mooring system solutions in order to reduce line tensions and hence loads transmitted into the WEC structure.

The cost of purchasing, installing and operating the mooring system (including anchorage) is repeatedly cited as a key issue. The data collected shows that WEC developers are generally open to innovative or novel solutions if they can be qualified with high-confidence and achieve cost reductions. The nylon rope case study presented in Section 3.3.3 demonstrates that the qualification process requires the input of a range of stakeholders including the supply chain, test houses, end-users and classification societies. They identify quick-connect systems as being a key area of development for this along with compliant mooring systems and low-cost novel anchoring strategies. Challenges are identified such as the dynamic nature of the system, electrical umbilical off-take, running mooring lines over sheaves, vertical loads at anchors in 'hard' sea beds, active/passive weather-vaning and active/passive storm survival strategies. Some or many of these challenges may be largely bespoke to the WEC sector. All of these areas could be deemed worthy of research and development projects.

7.1.3 Mooring & Foundation Innovations

The TRIZ approach to innovation generated over 200 ideas which were grouped and scored. Short-listed ideas were then analysed via a Pugh Matrix. The matrix identified and ranked 40 ideas considered worthy of further consideration. A large proportion of the ideas generated related to anchoring. The mooring & foundation case study highlighted that conventional GBA is unaffordable. However, the Pugh matrix identified a number of opportunities in the development of GBA's. If the mooring loads to a GBA can be reduced (e.g. via compliance), then this will improve their viability. GBA or hybrid solution may be an attractive solution for early WEC arrays which cannot tolerate the cost of offshore drilling vessels. Less specific ideas were generated in relation to innovative rock anchoring or drilling, although the lasso anchor is worthy of further consideration. There are clearly opportunities in the development of semi-autonomous underwater drilling units. While drag embedment anchoring is already highly evolved and very efficient in the right seabed conditions, there were a number of alternative ideas generated to provide drag embedment. In terms of reducing mooring loads, one relevant pathway is the utilisation of compliant line components (such as elastomeric moorings) which can provide high levels of axial compliance. Ideas were also generated in relation to mooring line active control and wave power absorption. There were quite few ideas generated in relation to biomimicry. Other ideas included piggy -backing the umbilical with the mooring line in addition to quick-release umbilical couplings (in the event of an extreme survival situation).

7.1.4 Mooring & Foundation Case Studies

The purpose of the scenario-based study was to show the techno-economic impact of mooring compliance on system cost and weight, including foundations. The impact was assessed for a range of WEC scales, water depths, footprints and foundation types. A comparison was conducted between two spread mooring system types with compliance provided by mooring line axial compliance (e.g. a semi-taut nylon-based system) and catenary geometry (e.g. a chain-based system). It was not possible to consider every type of mooring and the VOC confirmed that spread moorings are popular with the WEC sector. Furthermore, it was not possible to substantiate the cost of newer innovations (e.g. shock-absorbers) which could provide similar benefits to nylon. Nylon and chain were chosen to provide a useful benchmark demonstrating and quantifying the benefits of mooring compliance.

In virtually all cases the nylon based mooring was shown to attract lower peak line tension and was less expensive than the chain catenary equivalent, with the additional benefit of being lighter in terms of transportation and installation costs. In terms of peak mooring line loads and costs the benefit was less pronounced for the smallest buoy investigated (e.g. 100T compared to 1000T and 5000T displacement). For similar line MBL capacities, smaller mooring footprints can be adopted with nylon lines compared to chain lines. However smaller footprints will increase the vertical load component at the anchor which may or may not be desirable depending on the type of anchor selected. Conversely the compliance of a nylon mooring system can be further increased and peak loads reduced by increasing the mooring footprint at the expense of using up greater sea space. A softer mooring associated with a larger footprint will lead to greater excursions which could make power export via electrical umbilical more challenging if a permanent connection is required, however there is scope to develop quick and/or partial release connectors. When carrying out a like-for-like comparison of nylon and chain case studies the greatest benefit of using synthetic rope systems was observed for low footprint-water depth ratios featuring: i) similar maximum surge excursions, ii) lower line tensions and iii) lower total line costs. In terms of the relative LCOE there are significant benefits in adopting a mooring system which utilises compliant mooring components instead of chain, these improvements are even more significant when adopting DEAs or VLAs over conventional gravity base anchors.

In terms of relative comparison of LCOE between the synthetic rope and catenary chain cases at varying water depths, in all cases, the LCOE of the nylon cases are shown to be less than the equivalent LCOE of the catenary chain cases, demonstrating the potential for cost reduction by selecting synthetic mooring components. These calculations were based on a common installation cost centre. The installation-related benefits reported In Section 6 (in terms of installation time, cost and handling weight) are likely to be reflected in the installation LCOE cost. Further work is required to demonstrate if this is the case which will be possible once the WEC sector matures. In general, the gravity anchor cases demonstrate greater relative savings than the drag anchors and this is due to the influence of line tensions on the associated holding capacity requirements of the larger, bulky anchors.

As part of this cost study the percentage breakdown of mooring and foundation cost centre relative to corresponding LCOE were estimated for all device scales and line types. Whilst 10% is traditionally assumed for the mooring and foundation cost centre [120] and falls within the bounds of the results, the minimum and maximum values cover a large range with maximum % reaching ~49% for chain and ~39% for synthetic rope assuming conventional gravity-based anchors and as low as ~0.4% for the most compliant synthetic mooring with high efficiency DEAs.

It should also be noted that the relative merits of utilising compliant line materials may also potentially result in favourable reductions for other cost centres, e.g. the structural requirements of the device itself. Put simply, if peak line loads are reduced then it may be possible to opt for a lighter, more cost effective structure.

To assess the results against the current state of the sector, the results were matched against target or threshold values for total project CAPEX, as provided by [120]. The threshold levels for current development range between (£3,250 - £14,706 (£/kW)) with commercial targets ranging between (£2,194 - £7,394 (£/kW)). Expressed in terms of CAPEX per kW of device rating it was found that the range of calculated CAPEX/kW includes minimum values that are below the current and commercial deployment targets and these all correspond to synthetic rope cases. Conversely the maximum CAPEX/kW values all correspond to chain cases.

7.2 Opportunities for Cost Reduction, Innovation and Future R&D

The Landscaping Study has demonstrated that there are clear opportunities to make impact into the cost of energy of wave power through further development and innovation in mooring components (including lines, connecting and auxiliary hardware), foundations and associated subsystems. However due to the diverse nature of current WEC technologies and site conditions there are not singular innovations which will benefit all technologies. While some of the innovations could be tailored to the needs of the developer it is likely that some technologies will only be appropriate for certain WEC devices.

Opportunities for cost reduction exist through the development of existing technologies and new innovations. The requirements and priorities of the sector confirmed by the VOC survey correlate well with the opportunities for new innovation identified by TRIZ exercise. Opportunities for cost reduction include:

- Low cost easily installed and recovered anchors, particularly for rocky seabed.
- Further development of synthetic based mooring systems and shock-absorbers
- Cost effective weather vaning systems in order to reduce loads and optimise energy yield.
- Development of ropes with adequate fatigue life for bend over sheave applications
- Development of quick connect/disconnect systems for installation and recovery in order to improve availability (i.e. key connection interfaces including at top end, surface buoy or anchor)
- Design of marine installation practices and hardware to improve availability which are compatible with priority enabling mooring and foundation technology.
- Other opportunities include integrated umbilical and mooring line design and anchor sharing

The Mooring & Foundation case studies provided a useful cost benchmark for the development of shock absorber and new anchoring technology. This study considers two extremes of mooring system; chain catenary and taut synthetic. In practice, there may be hybrid moorings and different combinations which results in a total mass of line components which would fall within this range of ~50T to ~500T e.g. combinations of chain/wire, synthetic and shock absorber and buoys.

Not all of the pathways to reducing costs are technological in nature. It has been demonstrated that particularly well-established procedures (such as those associated with certification, qualification, testing, maintenance, monitoring and installation) may benefit from adaptation or the development of new procedures.

- Development of suitable codes and offshore guidance which is less conservative and more appropriate to the requirements of the sector.
- Development of suitable condition monitoring instrumentation, systems and practices which will ultimately help inform offshore guidance tailored to MRE sector.
- Addressing some of the commercialisation hurdles in terms of rope qualification and testing practices and product certification for specific WEC developments.
- Improved representation of ropes and shock-absorbers in WEC performance modelling software, commercial mooring software and physical small-scale (wave tank) testing.
- Development of fully-coupled global analysis tools (including hydrodynamics and foundations) for more accurate representation and optimisation of mooring systems.

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9 APPENDICES

Table 27: Device details

Device scale	BC1	BC2	BC4
Diameter/Draft ratio	3.483		
Displacement (T)	5000.000	1000.000	100.000
Displacement (m^3)	4878.049	975.610	97.561
Draft (m)	8.000	4.678	2.172
WPA (m^2)	609.756	208.534	44.927
Diameter (m)	27.863	16.295	7.563
Radius (m)	13.932	8.147	3.782
Total height (m)	16.000	9.357	4.343
Ixx, Iyy (T.m^2)	349280.909	23890.478	514.705
Izz (T.m^2)	485228.485	33189.162	715.039
rxx, ryy (m)	8.358	4.888	2.269
rzz (m)	9.851	5.761	2.674
Assumed VCG (m)	0.00	0.00	0.00
Dry/wet exposed area (m^2)	222.907	76.233	16.424

Table 28: Chain scenarios (anchor variations not shown). The green colour code is used to indicate scenarios where a mooring and foundation system solution was identified. A red colour code is used to indicate that a solution wasn't found for the particular scenario.

	Device scale			Water depth [m]				Footprint radius [m]				
Run	BC1	BC2	BC4	25.0	50.0	75.0	100.0	1000	750	500	250	100
BC1_CC_d25m_fp1000m	X			X				X				
BC1_CC_d50m_fp1000m	X				X			X				
BC1_CC_d75m_fp1000m	X					X		X				
BC1_CC_d100m_fp1000m	X						X	X				
BC1_CC_d25m_fp750m	X			X					X			
BC1_CC_d50m_fp750m	X				X				X			
BC1_CC_d75m_fp750m	X					X			X			
BC1_CC_d100m_fp750m	X						X		X			
BC1_CC_d25m_fp500m	X			X						X		
BC1_CC_d50m_fp500m	X				X					X		
BC1_CC_d75m_fp500m	X					X				X		
BC1_CC_d100m_fp500m	X						X			X		
BC1_CC_d25m_fp250m	X			X							X	
BC1_CC_d50m_fp250m	X				X						X	
BC1_CC_d75m_fp250m	X					X					X	
BC1_CC_d100m_fp250m	X						X				X	
BC2_CC_d25m_fp1000m		X		X				X				
BC2_CC_d50m_fp1000m		X			X			X				
BC2_CC_d75m_fp1000m		X				X		X				
BC2_CC_d100m_fp1000m		X					X	X				
BC2_CC_d25m_fp750m		X		X					X			
BC2_CC_d50m_fp750m		X			X				X			
BC2_CC_d75m_fp750m		X				X			X			
BC2_CC_d100m_fp750m		X					X		X			
BC2_CC_d25m_fp500m		X		X						X		
BC2_CC_d50m_fp500m		X			X					X		
BC2_CC_d75m_fp500m		X				X				X		
BC2_CC_d100m_fp500m		X					X			X		
BC2_CC_d25m_fp250m		X		X							X	
BC2_CC_d50m_fp250m		X			X						X	
BC2_CC_d75m_fp250m		X				X					X	
BC2_CC_d100m_fp250m		X					X				X	
BC4_CC_d25m_fp1000m			X	X				X				
BC4_CC_d50m_fp1000m			X		X			X				
BC4_CC_d75m_fp1000m			X			X		X				
BC4_CC_d100m_fp1000m			X				X	X				
BC4_CC_d25m_fp750m			X	X					X			
BC4_CC_d50m_fp750m			X		X				X			

		Device scale			Water depth [m]				Footprint radius [m]				
	BC4_CC_d75m_fp750m			X			X			X			
	BC4_CC_d100m_fp750m			X				X		X			
	BC4_CC_d25m_fp500m			X	X						X		
	BC4_CC_d50m_fp500m			X		X					X		
	BC4_CC_d75m_fp500m			X			X				X		
	BC4_CC_d100m_fp500m			X				X			X		
	BC4_CC_d25m_fp250m			X	X							X	
	BC4_CC_d50m_fp250m			X		X						X	
	BC4_CC_d75m_fp250m			X			X					X	
	BC4_CC_d100m_fp250m			X				X				X	
	BC4_CC_d25m_fp100m			X	X								X
	BC4_CC_d50m_fp100m			X		X							X
	BC4_CC_d75m_fp100m			X			X						X
	BC4_CC_d100m_fp100m			X				X					X

Table 29: Synthetic rope scenarios (anchor variations not shown). The green colour code is used to indicate scenarios where a mooring and foundation system solution was identified. A red colour code is used to indicate that a solution wasn't found for the particular scenario. EA/BL is the axial stiffness to break load ratio of the rope.

	Device scale			EA/BL		Water depth [m]				Footprint radius [m]				
Run	BC1	BC2	BC4	8	4	25.0	50.0	75.0	100.0	1000	750	500	250	100
BC1_TR_d25m_fp1000m_EABL8	X			X		X				X				
BC1_TR_d50m_fp1000m_EABL8	X			X			X			X				
BC1_TR_d75m_fp1000m_EABL8	X			X				X		X				
BC1_TR_d100m_fp1000m_EABL8	X			X					X	X				
BC1_TR_d25m_fp750m_EABL8	X			X		X					X			
BC1_TR_d50m_fp750m_EABL8	X			X			X				X			
BC1_TR_d75m_fp750m_EABL8	X			X				X			X			
BC1_TR_d100m_fp750m_EABL8	X			X					X		X			
BC1_TR_d25m_fp500m_EABL8	X			X		X						X		
BC1_TR_d50m_fp500m_EABL8	X			X			X					X		
BC1_TR_d75m_fp500m_EABL8	X			X				X				X		
BC1_TR_d100m_fp500m_EABL8	X			X					X			X		
BC1_TR_d25m_fp250m_EABL8	X			X		X							X	
BC1_TR_d50m_fp250m_EABL8	X			X			X						X	
BC1_TR_d75m_fp250m_EABL8	X			X				X					X	
BC1_TR_d100m_fp250m_EABL8	X			X					X				X	
BC2_TR_d25m_fp1000m_EABL8		X		X		X				X				
BC2_TR_d50m_fp1000m_EABL8		X		X			X			X				
BC2_TR_d75m_fp1000m_EABL8		X		X				X		X				
BC2_TR_d100m_fp1000m_EABL8		X		X					X	X				
BC2_TR_d25m_fp750m_EABL8		X		X		X					X			
BC2_TR_d50m_fp750m_EABL8		X		X			X				X			
BC2_TR_d75m_fp750m_EABL8		X		X				X			X			
BC2_TR_d100m_fp750m_EABL8		X		X					X		X			
BC2_TR_d25m_fp500m_EABL8		X		X		X						X		
BC2_TR_d50m_fp500m_EABL8		X		X			X					X		
BC2_TR_d75m_fp500m_EABL8		X		X				X				X		
BC2_TR_d100m_fp500m_EABL8		X		X					X			X		
BC2_TR_d25m_fp250m_EABL8		X		X		X							X	
BC2_TR_d50m_fp250m_EABL8		X		X			X						X	
BC2_TR_d75m_fp250m_EABL8		X		X				X					X	
BC2_TR_d100m_fp250m_EABL8		X		X					X				X	
BC4_TR_d25m_fp1000m_EABL8			X	X		X				X				
BC4_TR_d50m_fp1000m_EABL8			X	X			X			X				
BC4_TR_d75m_fp1000m_EABL8			X	X				X		X				
BC4_TR_d100m_fp1000m_EABL8			X	X					X	X				
BC4_TR_d25m_fp750m_EABL8			X	X		X					X			
BC4_TR_d50m_fp750m_EABL8			X	X			X				X			

		Device scale			EA/BL		Water depth [m]				Footprint radius [m]				
	BC4_TR_d75m_fp750m_EABL8			X	X				X			X			
	BC4_TR_d100m_fp750m_EABL8			X	X					X		X			
	BC4_TR_d25m_fp500m_EABL8			X	X		X						X		
	BC4_TR_d50m_fp500m_EABL8			X	X			X					X		
	BC4_TR_d75m_fp500m_EABL8			X	X				X				X		
	BC4_TR_d100m_fp500m_EABL8			X	X					X			X		
	BC4_TR_d25m_fp250m_EABL8			X	X		X							X	
	BC4_TR_d50m_fp250m_EABL8			X	X			X						X	
	BC4_TR_d75m_fp250m_EABL8			X	X				X					X	
	BC4_TR_d100m_fp250m_EABL8			X	X					X				X	
	BC4_TR_d25m_fp100m_EABL8			X	X		X								X
	BC4_TR_d50m_fp100m_EABL8			X	X			X							X
	BC4_TR_d75m_fp100m_EABL8			X	X				X						X
	BC4_TR_d100m_fp100m_EABL8			X	X					X					X
	BC1_TR_d25m_fp1000m_EABL4	X				X	X				X				
	BC1_TR_d50m_fp1000m_EABL4	X				X		X			X				
	BC1_TR_d75m_fp1000m_EABL4	X				X			X		X				
	BC1_TR_d100m_fp1000m_EABL4	X				X				X	X				
	BC1_TR_d25m_fp750m_EABL4	X				X	X					X			
	BC1_TR_d50m_fp750m_EABL4	X				X		X				X			
	BC1_TR_d75m_fp750m_EABL4	X				X			X			X			
	BC1_TR_d100m_fp750m_EABL4	X				X				X		X			
	BC1_TR_d25m_fp500m_EABL4	X				X	X						X		
	BC1_TR_d50m_fp500m_EABL4	X				X		X					X		
	BC1_TR_d75m_fp500m_EABL4	X				X			X				X		
	BC1_TR_d100m_fp500m_EABL4	X				X				X			X		
	BC1_TR_d25m_fp250m_EABL4	X				X	X							X	
	BC1_TR_d50m_fp250m_EABL4	X				X		X						X	
	BC1_TR_d75m_fp250m_EABL4	X				X			X					X	
	BC1_TR_d100m_fp250m_EABL4	X				X				X				X	
	BC2_TR_d25m_fp1000m_EABL4		X			X	X				X				
	BC2_TR_d50m_fp1000m_EABL4		X			X		X			X				
	BC2_TR_d75m_fp1000m_EABL4		X			X			X		X				
	BC2_TR_d100m_fp1000m_EABL4		X			X				X	X				
	BC2_TR_d25m_fp750m_EABL4		X			X	X					X			
	BC2_TR_d50m_fp750m_EABL4		X			X		X				X			
	BC2_TR_d75m_fp750m_EABL4		X			X			X			X			
	BC2_TR_d100m_fp750m_EABL4		X			X				X		X			
	BC2_TR_d25m_fp500m_EABL4		X			X	X						X		
	BC2_TR_d50m_fp500m_EABL4		X			X		X					X		
	BC2_TR_d75m_fp500m_EABL4		X			X			X				X		

		Device scale			EA/BL		Water depth [m]				Footprint radius [m]				
	BC2_TR_d100m_fp500m_EABL4		X			X				X			X		
	BC2_TR_d25m_fp250m_EABL4		X			X	X							X	
	BC2_TR_d50m_fp250m_EABL4		X			X		X						X	
	BC2_TR_d75m_fp250m_EABL4		X			X			X					X	
	BC2_TR_d100m_fp250m_EABL4		X			X				X				X	
	BC4_TR_d25m_fp1000m_EABL4			X		X	X				X				
	BC4_TR_d50m_fp1000m_EABL4			X		X		X			X				
	BC4_TR_d75m_fp1000m_EABL4			X		X			X		X				
	BC4_TR_d100m_fp1000m_EABL4			X		X				X	X				
	BC4_TR_d25m_fp750m_EABL4			X		X	X					X			
	BC4_TR_d50m_fp750m_EABL4			X		X		X				X			
	BC4_TR_d75m_fp750m_EABL4			X		X			X			X			
	BC4_TR_d100m_fp750m_EABL4			X		X				X		X			
	BC4_TR_d25m_fp500m_EABL4			X		X	X						X		
	BC4_TR_d50m_fp500m_EABL4			X		X		X					X		
	BC4_TR_d75m_fp500m_EABL4			X		X			X				X		
	BC4_TR_d100m_fp500m_EABL4			X		X				X			X		
	BC4_TR_d25m_fp250m_EABL4			X		X	X							X	
	BC4_TR_d50m_fp250m_EABL4			X		X		X						X	
	BC4_TR_d75m_fp250m_EABL4			X		X			X					X	
	BC4_TR_d100m_fp250m_EABL4			X		X				X				X	
	BC4_TR_d25m_fp100m_EABL4			X		X	X								X
	BC4_TR_d50m_fp100m_EABL4			X		X		X							X
	BC4_TR_d75m_fp100m_EABL4			X		X			X						X
	BC4_TR_d100m_fp100m_EABL4			X		X				X					X