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MOORINGS & CONNECTION SYSTEMS COST METRICS

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CONTENTS

1. Executive summary 5
2. Introduction 7
2.1 Additional mooring design drivers 8
3. Mechanical moorings & connection components 9
3.1 Bespoke fabrications 9
3.1.1 The TLA and tether hooks 9
3.1.2 Tether hook profile vs machining costs 9
3.1.3 Wet-mate junction box 10
3.2 Bespoke buoyancy assemblies 11
3.3 Additional TLA components 12
3.4 Tether lines 12
3.5 Chain sections 13
3.6 Wire sections 14
3.6.1 Low rotation specialist rope 14
3.6.2 Standard IWRC wire ropes 15
3.7 Connection plates 15
3.8 Shackle connections 15
3.9 Anchors 17
3.10 Clump weights 18
4. Subsea electrical infrastructure 19
4.1 Wet-mate connectors 19
4.1.1 Power wet-mate 19
4.1.2 Communication wet-mate 20
4.1.3 Subsea additional array connector requirements 20
4.2 Dynamic cable 21
4.3 Cable buoyancy, ballast & touchdown clump 23
4.4 Bend stiffeners 24
5. Moorings installation indicitive cost 25
6. Machine installation indicitive costs 27
7. Machine located raipd connection components 28
7.1 Mechanical latch components 28
7.2 Hydraulic latch components 28

7.3 Wet mate carriage 29
7.4 Yoke end cameras 29
8. Example mooring & connection systems 30
8.1 Alterations for different mooring specifications 31
8.1.1 Pelamis machine configuration 31
8.1.2 Water depth increases 32
8.1.3 Yaw system changes 32
8.1.4 Array considerations 33
8.2 P2 mooring costs (50m water depth, 6.6kV, passive yaw) 34
8.4 Indicative P3 mooring costs (70m water depth, 11kV, active yaw) 35
8.5 Indicative wave farm mooring costs (130m water depth, 11kV, active yaw) 36
8.6 Graphical representations of Mooring Infrastructure costs 37

ABBREVIATIONS

CNC	Computerised Numerical Control
CSA	Cross Sectional Area
EMEC	European Marine Energy Centre
FIST	Fibre In Steel Tube
IWRC	Independent wire rope core (a type of wire rope)
LCoE	Levalised Cost of Energy
MBL	Minimum Break Load
MOQ	Minimum Order Quantity
O&M	Operations & Maintenance
P2-001	Pelamis P2 device supplier to EON
P2-002	Pelamis P2 device supplier to Scottish Power Renewables
PTO	Power Take-Off
PU	Polyurethane
PWP	Pelamis Wave Power
ROV	Remote Operated Vehicle
SAEP	Senior Authorized Electrical Person
SLAC	Stud Link Anchor Chain
SWL	Safe Working Load
TLA	Tether Latch Assembly
ULS	Ultimate Limit State
WEC	Wave Energy Convertor
WMC	Wet Mate Carriage
WMJB	Wet Mate Junction Box

1. EXECUTIVE SUMMARY

This report looks at the Pelamis mooring system and the cost metrics associated with the major components therein. The Pelamis mooring spread is a chain based catenary mooring spread including primary and secondary mooring systems in conjunction with electrical export and communication components. The catenary mooring system utilised standard embedment anchors, with chain lines on the sea bed to give the required spring force, and synthetic tethers rising up through the water column to the machine connection point. At this location, the necessary equipment to enable the rapid connection and disconnection of the Pelamis WEC to and from its moorings was located. A secondary mooring line, the yaw line, provided heading restraint and prevented the Pelamis from weathervaning beyond the limits defined.

The majority of costs used in this analysis are those accumulated by PWP for moorings components for the P2 mooring spreads deployed at the EMEC site in Orkney in 2010 and 2011 with the actual purchases being made from 2009 onwards. Some items in the system were replaced over the course of the P2 operations programme, procured as spares, or for ongoing operations and these later costs have been included if appropriate.

Each major component in the Pelamis mooring system is considered in the document and the most appropriate cost metric for that component defined. Appropriate metrics for each of the major components are then brought together to provide example costings for three indicative systems, namely;

1. Single device, 50m water depth, 6.6kV electrical connection, passive yaw system (i.e. the P2 system)
2. Single device, 70m water depth, 11kV electrical connection, active yaw system (i.e. indicative of a single P3 mooring)
3. 10 machine wave farm, 130m water depth, 11kV electrical connection in a wave farm infrastructure, active yaw system (i.e. indicative of a wave farm P3 mooring)

Each mooring spread was split into 4 sub-systems which were costed separately. The high level costs for these indicative mooring spreads are shown in the table below.

	Seabed Primary Mooring Components	Tether Components	Secondary Mooring Components	Electrical Infrastructure	TOTAL
P2 Indicative Single Mooring	£183k	£82k	£23k	£291k	**£579k**
P3 Indicative Single Mooring	£200k	£114k	£67k	£304k	**£685k**
P3 Indicative Wave Farm (avg. per mooring)	£200k	£131k	£68k	£507k	**£906k**

Table 1: High level estimated costs for indicative mooring systems analysed.

It is important that these costs are not considered in isolation. The cost of a mooring system must be considered in the context of all the other costs associated with the cost of energy. The lowest cost option for a component does not necessarily result in the lowest LCoE for a WEC as a whole. System reliability, availability, efficiency, and impacts on O&M strategy etc. are also fundamental factors which need to be considered when designing systems and selecting components, and these were all considered when selecting components to be included in the Pelamis mooring system. For example, the introduction of an active yaw system increases mooring capital expenditure but the increased revenue from performance gains should more than offset this. Similarly, additional expenditure on electrical infrastructure for a wave farm improves the reliability of the electrical connection and additional wet-mate connectors reduce installation and O&M costs so overall cost savings can be realised.

With this in mind, although it is not the focus of this document, some indicative costs for the installation of the moorings spread and a machine installation and removal cycle have been included based on PWP's experience of such operations. It is estimated that installing a single P3 mooring spread, using multicat vessels where possible, would cost approximately £700k. This includes, delivery and logistics costs, personnel costs, vessel hire costs and temporary equipment costs. It is apparent that moorings installation costs are comparable to the costs of the moorings components themselves.

The costs to PWP of a single P2 machine installation and removal cycle has been estimated to be in the region of £25k based on a 3hour tow to site. Although not an insignificant amount, this relatively small number compared to the moorings installation costs is only achievable thanks to the development by PWP of the rapid connection and disconnection system. This enabled machine installation to be completed in around 90minutes and disconnection from the moorings and electrical umbilical to be achieved in less than 10minutes.

There are some other key points that should be highlighted from the analysis undertaken.

- For the single P2 and P3 mooring systems the electrical infrastructure cost is roughly equal to the costs of the mechanical mooring components. However, the proportion of overall costs attributable to the electrical infrastructure is greater for a wave farm. This is primarily due to a tripling of the number of wet mate connectors required in order to interconnect multiple machines together. Operationally, it would be impossible to deploy all the wet mate junction boxes with pre-installed cables together and the flexibility that wet-mate connectors allow is imperative to achieve a reasonable electrical infrastructure installation process.
- The dominant individual cost of the Pelamis mooring spread is the dynamic cable by a considerable margin accounting for between 20% and 30% of the overall costs. Thereafter, as expected due to the large mass, chain is next accounting for 15-20% of the mooring spread cost. Anchors, shackles, the TLA and tether hook assemblies each account for 4-6% of the costs.
- It has been noted in this report that there is significant cost associated with machining components compared to just profiling and fabrication. Using the tether hooks as an example, material and profiling of the main hook component accounted for only 20% of the final assembly cost. 31% of the cost was attributed to the accurate machining of this component and the remainder for the detailed machining and manufacture of the small and detailed mechanism components.

Appropriate cost metrics have been derived for each of the major components of the mooring spread and are presented throughout the document. For the majority of components the cost per unit mass is the most relevant metric although cost per metre, cost per tonne safe working load and unit costs are also used. The cost metrics derived throughout the document are based on the following assumptions:

- All costs are based on purchase of a single moorings spread at the relevant quantities with the exception of the wet-mate connectors for which PWP had break points for different quantities. Economies of scale could be realised for some other items as quantities grow but the savings achievable would predominantly be in bespoke mooring components rather than standard items.
- Development and system assembly costs (e.g. labour, design effort, fabrication space) have not been included in this analysis. Although these costs are not directly included in the metrics given, the impact of these on the overall cost of a moorings spread can be considerable.
- Costs have not been adjusted to account for inflation or differences in commodity prices.
- Where accurate cost metrics can be defined they have been, although there is some element of estimation in many metrics. Any estimates made are based on sound engineering judgement and experience of how costs have varied over the history of the Pelamis development.

2. INTRODUCTION

The chained based catenary mooring system developed by PWP for the Pelamis WEC is illustrated in Figure 1 below. It consists of a primary mooring system, a secondary mooring system (the yaw line), rapid connection and disconnection components, and an electrical export cable and associated infrastructure. This report looks at the costs associated with each of the major components of this mooring spread.

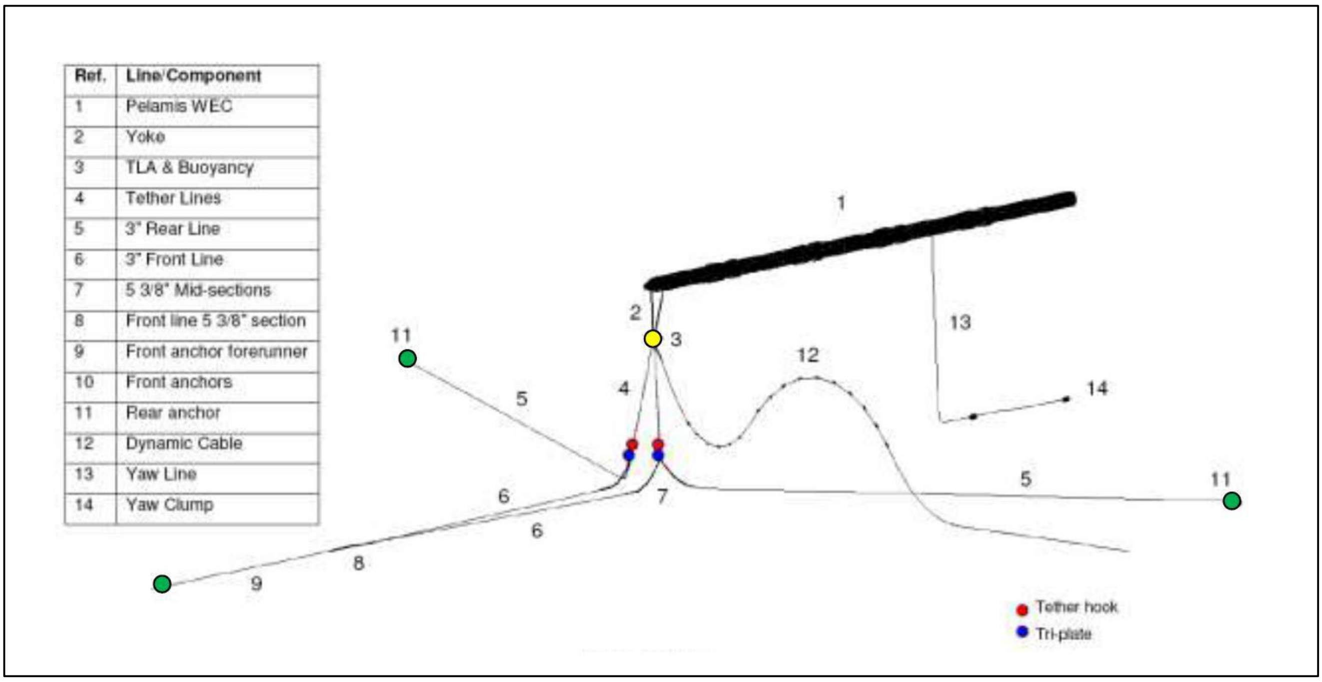


Figure 1: Schematic of the Pelamis catenary mooring system

The mooring system illustrated above and used for reference costs throughout this document is the P2-002 mooring spread that was deployed at EMEC in 2011. There are slight differences between this and the P2-001 moorings but the vast majority of components are the same and costs associated with the P2-001 mooring infrastructure deployed in 2010 have also been included where possible. The P2 mooring system was designed for a 50m water depth site, with a soft sediment sea bed. The export voltage of the P2 devices was 6.6kV and the yaw system was passive and only limited weathervaning when the machine reached the defined limits.

The mooring system pictured above can be easily adapted for deeper water by increasing the lengths of the tether sections that rise up through the water column. Similarly, individual components can also be adapted, exchanged or up-rated to increase the export voltage or to introduce an active yaw system that is capable of controlling machine heading when desired. How the system would be altered for different site characteristics or conditions is discussed in more depth in section 8 of this document. Appropriate metrics from the rest of the document for each of the major components are then brought together to provide example costings for three indicative systems.

1. Single device, 50m water depth, 6.6kV electrical connection, passive yaw system (i.e. the P2 system)
2. Single device, 70m water depth, 11kV electrical connection, active yaw system (i.e. indicative of a single P3 mooring)
3. 10 machine wave farm, 130m water depth, 11kV electrical connection in a wave farm infrastructure, active yaw system (i.e. indicative of a wave farm P3 mooring)

2.1 ADDITIONAL MOORING DESIGN DRIVERS

The cost metrics presented throughout this document are derived or estimated from known P2 costs for moorings components. The mooring design was selected based on optimising the Levelised Cost of Energy (LCoE) for the Pelamis as a whole. The lowest up-front cost components does not necessarily lead to the most commercially beneficial project. For example, the inclusion of the bespoke, expensive connection and disconnection system increases capital expenditure on the moorings. However, it enables the machine to be installed quickly, in more energetic sea conditions and with only modest vessel requirements. This results in availability increases of the machine and reduced O&M costs and an overall reduction in LCoE. Similarly, the inclusion on an active yaw system results is performance benefits that increase revenue over the project life time.

The additional drivers, as well as cost, that need to be considered when selecting components include:

- WEC availability
- Reliability
- Power capture
- Fault tolerance & redundancy
- Impact on O&M costs & strategy
- Impact on WEC major structural costs & complexity

It is not always obvious how different solutions impact on each of these drivers and, subsequently, how these drivers impact on the overall project economics. For example, a cable selected purely based on the expected maximum power output will not necessarily be the optimal size with respect to average transmission efficiency. The occurrence weighted output, based on the time spent in different power regimes, need to be considered along with other factors to determine the optimal cable size.

3. MECHANICAL MOORINGS & CONNECTION COMPONENTS

3.1 BESPOKE FABRICATIONS

Three main bespoke fabrications form part of the Pelamis mooring system, namely the TLA body, the tether hooks, and the wet-mate junction box (WMJB). It is not possible to define a single metric for all three units combined since the WMJB is designed as a pressurised volume and, as such, the fabrication process included additional steps to pressure and leak test the unit. The relative cost of the WMJB is therefore higher than the other two fabrications and they have been treated separately in this report.

3.1.1 THE TLA AND TETHER HOOKS

The cost and mass of the TLA and tether hooks are shown in the table below. Both were made out of standard steel plate and/or pipe and did not contain specialist materials.

	Cost (nearest £100)	Mass	Cost / kg
TLA Structural Components	£15,100	1350kg	£11.20
Tether hooks	£5,500	520kg	£10.60
Combined	**£20,600**	**1870kg**	**£11/kg**

Table 2: Fabricated mooring components costs and metrics

The final cost per unit weight for the individual fabrications is very similar. The manufacture of both assemblies requires a combination of welding, plate profiling and more detailed machining tasks.

Interestingly, this cost is comparable to the cost per kilogram of the integrated hydraulic cylinder assembly (including manifolds and bearings) and rod end bearing assemblies detailed in the PTO cost metrics report (SEC-D-006), which ranged from £10.80/kg to £13.70/kg. This therefore seems to be a fairly general metric that can be applied to large machined assemblies of this nature.

3.1.2 TETHER HOOK PROFILE VS MACHINING COSTS

It is useful to understand the additional cost that machining adds. The tether hooks were profiled and machined separately therefore enabling this difference to be illustrated. Two separate purchase orders were issued, one for the initial profiling of the hook from thick plate material and a second for the accurate machining of the hook thereafter. The mechanism's machined and fabricated items were procured separately as well. The costs associated with each are included in Table 3 below. It can be seen that the overall cost of the tether hook assembly is roughly evenly split between the hook itself and the mechanism components. However, the cost per kilogram of the small machined components was over twice that of the hook. Tooling set-up and machining time has a major impact here. This high cost of machining can also be seen when the hook cost is broken down into profile cutting (typically CNC laser, oxy-acetylene, waterjet or plasma cutting) and machining components. The rough profiling of the hook was relatively cheap but the subsequent machining process more than doubled the price. The final hook cost was over 250% that of the rough profiled hook alone.

	Cost (nearest £100)	Mass (kg)	% of Cost	Cost/kg
Hook Cost Total	**£2,800**	360kg	**51%**	**£7.80/kg**
Hook Cost (profiling)	£1,100		20%	£3.10/kg
Hook Cost (machining)	£1,700		31%	
Additional Hook Items	**£2,700**	**160kg**	**49%**	**£17/kg**
Hook Assembly Total	**£5,500**	**360kg**	**-**	**£10.60/kg**

Table 3: Profile cutting vs machining costs

3.1.3 WET-MATE JUNCTION BOX

The WMJB is the sealed electrical box in which the dynamic cable is terminated and the electrical connections to the wet-mate connectors are made. The structure includes the box and lid, a separately sealed internal communications junction box, the alignment spikes to ensure alignment with the yoke-mounted wet mate carriage (WMC), the cable penetrator plate, and the umbilical strain termination can. The total cost of this assembly was £11,700. The calculated cost metrics for this assembly can be seen in Table 4 below.

	Cost (nearest £100)	Mass	Cost / kg
WMJB Assembly Combined	**£11,700**	**469kg**	**£25/kg**

Table 4: WMJB fabrication costs and metrics

This component requires a high level of accurate machining which increases the cost substantially. This level of detail is required for two reasons; firstly, the dimensional accuracy of this fabrication is important to ensure correct alignment and engagement with the yoke mounted wet mate carriage during machine installation, and secondly, accurate machining is required in order to ensure the internal volume remains sealed from seawater for the life of the project. This is an extremely important characteristic to ensure machine availability since recovery and maintenance of this assembly is difficult given its location. Further steps were taken before final assembly to ensure the integrity of the seals and welds in the structure. This included both hydrostatic testing where the unit was filled with water and checked for leaks, and hydrogen gas leak testing where it was pressurised to a low pressure with a 95%N_2 / 5%H_2 gas mix and “sniffed” for leaks using a very sensitive hydrogen detector. Detection of even very minor flaws that could be problematic over time is possible and is an important step to ensure long term reliability. The cost of these tests was included in the price of fabrication increased the cost per kilogram further.

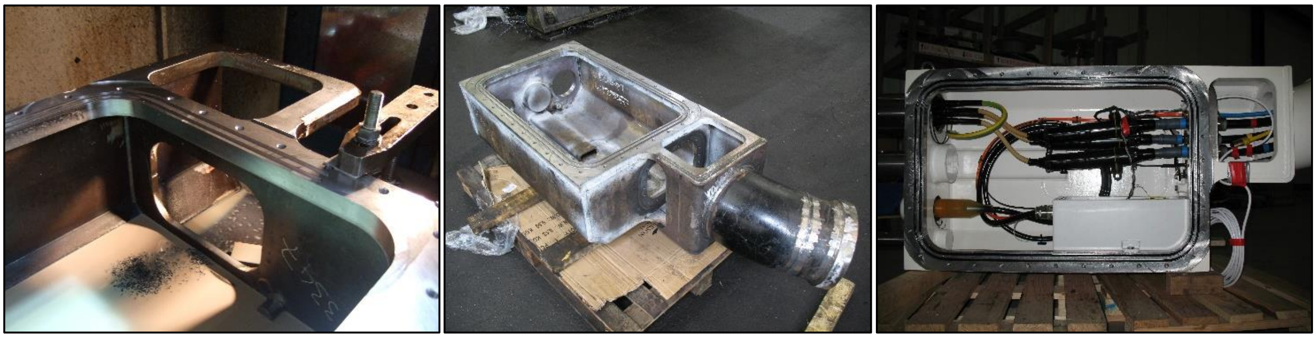


Figure 2: WMJB machining and fabrication. Many detailed machining processes were required to ensure sealing integrity of the complete unit and dimensional accuracy to ensure correct alignment with wet mate carriage on yoke end. The whole unit was hydrostatically tested and leak tested with a hydrogen ‘sniffer’ before being painted and populate with the internal components.

The calculated cost metric has been used in the calculation of costs for example mooring infrastructures in section 8 of this report. The P2 WMJB would not be suitable for use in a WEC array. In an array each WMJB must accept 2 dynamic cables to enable electrical connection between the machines. The size of the WMJB in a WEC array would therefore have to be increased to allow for additional electrical connections between adjacent devices. Doubling the width of the WMJB to allow for the additional power and communication connections would double the internal volume but does not double the mass of the fabrication. The additional mass is estimated to be only 60% more than the existing WMJB. This has been used in the example system costs to estimate the cost of a WMJB required for an array configuration. Increases in the TLA buoyancy to offset the added mass of the WMJB have also been included.

3.2 BESPOKE BUOYANCY ASSEMBLIES

The TLA buoyancy unit is constructed from Divinycell H100 closed cell foam sheet (depth rating approx. 165m) that are CNC waterjet profile cut then bonded together into the correct shape and fibreglass coated to provide individual complete buoyancy units. The TLA buoyancy manufacturing process can be seen in the images below. The cost of each stage of the process is shown in Table 5 thereafter. P2-002 TLA buoyancy costs have been included in this table but the same metrics apply to the slightly different P2-001 TLA buoyancy.

PWP investigated a number of methods for the manufacture of the TLA buoyancy units and found this to be by far the most cost effective. The more standard method for manufacture of buoyancy modules is to injection mould the outer shell and then fill the internal volume with closed cell buoyancy foam. This is a well understood and successful method of construction but for the complex shapes required in the TLA and given the small volumes of manufacture required, this cost of such units are prohibitive. The method employed by PWP for TLA buoy construction enables the buoys to be manufactured to a high degree of accuracy at a reasonable cost. It also has the advantage that even if the outer shell becomes damaged the foam core is rated to a higher depth than the normal operating depth, thus the overall buoyancy of the unit will be maintained.

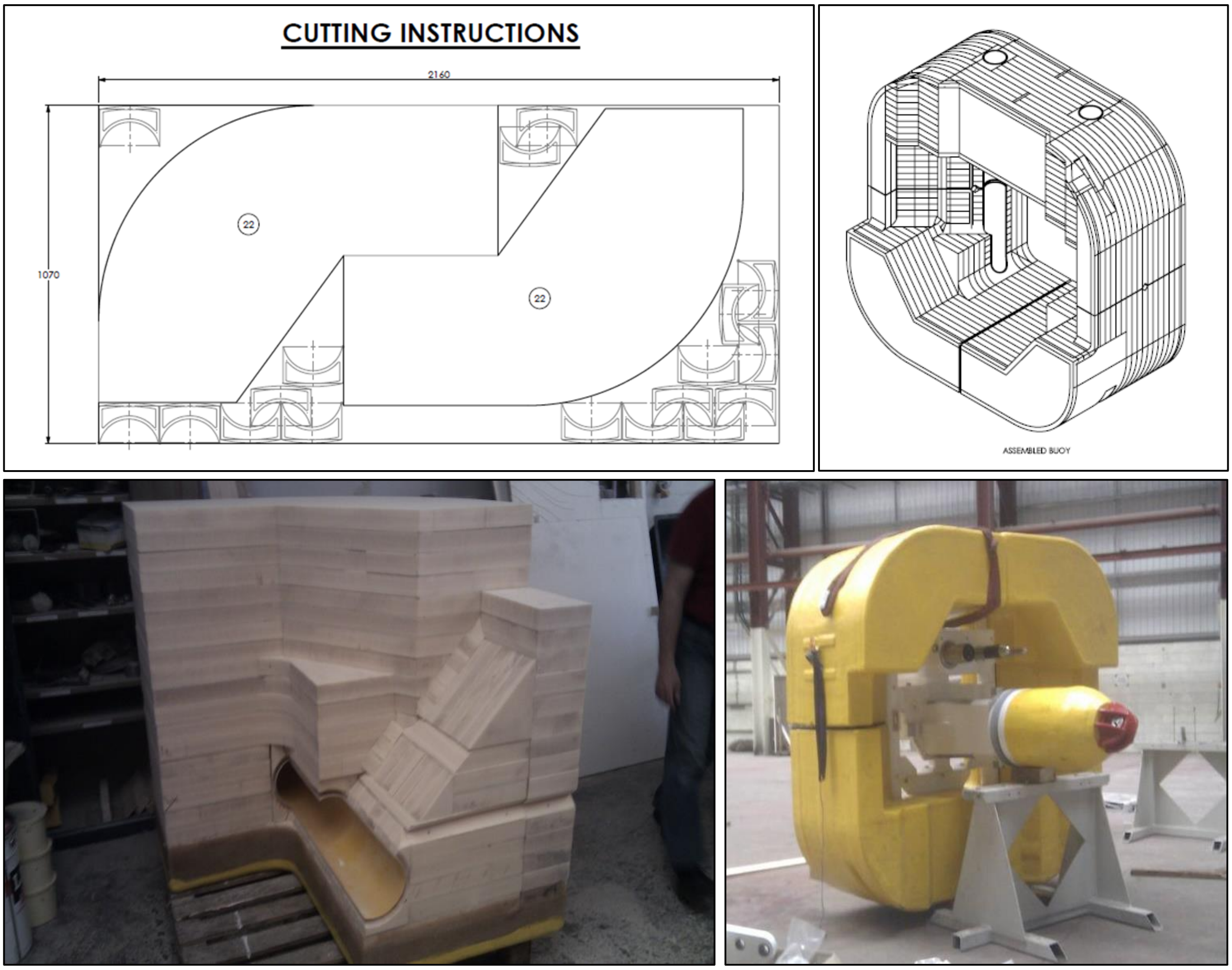


Figure 3: TLA buoyancy assembly process. First, Divinycell H100 sheets are waterjet cut (top left) and assembled into the shape of the TLA buoy required (top right, bottom left). The assembly is then coated in fibreglass to form single buoyancy modules.

	P2-002 Cost (nearest £100)	Mass / Volume	Cost Metric
Buoyancy Foam	£10,400	650kg	£16/kg
Water Jet Cutting	£3,300		
Assembly & Coating	£6,900	560kg	
Combined	**£20,600**	**1210kg**	**£37/kg**
		5.2m^3	**£4000/m^3**

Table 5: Buoyancy module assembly stage costs and overall metrics.

3.3 ADDITIONAL TLA COMPONENTS

In addition to the main TLA fabrication, WMJB and TLA buoyancy there are a number of other components that are part of the overall TLA assembly. The most notable of these components is the fibreglass bullnose. This is manufactured in a similar way to TLA buoyancy. Divinycell H100 sheets are cut and built up into the rough shape of the bullnose. This is then coated with fibreglass (over 80mm thick in places to provide the required strength) before being machined down to the final profile. This process is illustrated in the pictures below.

Figure 4: Manufacture of the fibreglass bullnose is similar to that of the TLA buoy. Profiled Divinycell sheet make up the rough shape which is then over moulded with fibreglass before being machined down to an accurate profile.

The costs of the additional items required to complete the TLA assembly are shown in Table 6 below. These have been treated as fixed costs in the example mooring infrastructure costs in section 8.

	Cost (nearest £100)	Mass
Fiberglass bullnose (excluding steelwork)	£1,500	200kg
Bullnose attachment, structure & ROV masterlink	£1,500	95kg
Miscellaneous fasteners, ratchet straps etc	£1,500	-
TOTAL	**£4,500**	**-**

Table 6: Fixed costs of additional TLA items

3.4 TETHER LINES

The synthetic tethers used in the Pelamis mooring system were supplied by Lankhorst Ropes. The ø125mm Gama98 polyester rope tethers are made from high efficiency sub rope cores laid parallel within an outer braided jacket. The rope diameter used has a minimum break load (MBL) of 450Te. Filter elements are included between the jacket and sub-rope cores. These are effective at filtering out particles greater that 5microns whilst allowing free flooding of the rope. Given the sand and sediment that is present in the water column this is an important feature to ensure long-term retention of rope strength.

The P2 synthetic tethers were each 18m in length and cost £5,390 each. Based on discussions with the manufacturer this cost can be roughly split into the rope material cost and one off costs per tether. The one off unit costs include the cost of the thimbles at each end of the rope as well as the cost of splicing and coating of the thimbles and splice in a PU coating. This amounts to approximately £4000 per tether assembly. The make-up of the rope and elements of the completed assembly are shown in Figure 5. The thimbles used were modified K3-B thimbles with an extra central bush to suit the shackles that are used to connect the tethers into the mooring system.

The remaining cost is attributable to the cost of rope itself. An indicative cost of tethers of different lengths can therefore be calculated. Since these are the components that rise up through the water column from the seabed in the Pelamis mooring spread any change in water depth is mostly taken up by altering the length of these lines. The cost per kilogram has been calculated to allow indicative costs of different diameter Gama98 ropes to be estimated although it should be noted that larger diameter ropes will also incur higher unit costs for thimbles and splicing.

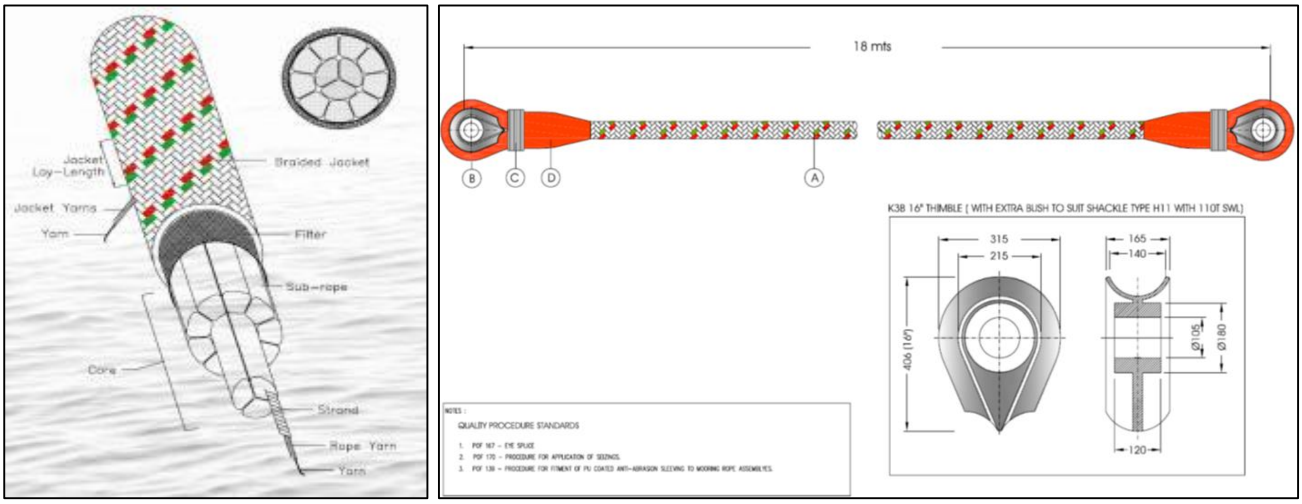


Figure 5: Tether rope lay-up and full assembly detail

	Metrics
Tether Assembly Unit Cost (thimbles, splicing, PU coating etc)	£4000
Ø125mm Gama98 Rope cost (£/m)	£80 per m
Ø125mm Gama98 Rope mass (kg/m)	10.8kg
Gama98 Rope indicative cost (£/kg)	£7.40 per kg

Table 7: Tether cost metrics

3.5 CHAIN SECTIONS

Chain is used throughout the Pelamis mooring infrastructure. The total mass of chain used in the P2 mooring in EMEC was 120Te. The chain used is stud link anchor chain (SLAC) and predominantly consists of 2 sizes, 76mm and 137mm diameter. The larger diameter chain connected into the tether hooks on the front and rear mooring lines is used to provide additional mass in the moorings at this location. As these chains are gradually lifted off the seabed the mooring load increases and the restoring force provided by the moorings increases providing a useful spring component to the mooring system.

The cost metrics derived and shown in Table 8 below are the average of all chain sections purchased over the last 6 years by PWP. It is not surprising that chain is the cheapest per kilogram of all components studied in this report with the lowest prices being not much more than that average cost of steel. The price per kilogram ranges from around £0.70/kg to £1.10/kg over an assortment of sizes and lengths. All chains that formed part of the load path in the moorings were purchased with appropriate certification. The chain sections during deployment are visible in Figure 6.

Cost Metric	**Value**
Cost / kg	£0.95/kg
Cost / Te (break load) per m length	£0.26/Te BL per m

Table 8: Mooring chain cost metrics

Figure 6: Mooring chain during deployment

In addition to the above mooring chains, a number of chain sections were bought for use as clump weights during marine operations or for the yaw line assembly. These chains did not need to be certified or rated for a specific load and could therefore be purchased as used chain without certification which reduced their cost considerably. The average cost of these chains was £330/Te (also detailed in section 3.10).

3.6 WIRE SECTIONS

3.6.1 LOW ROTATION SPECIALIST ROPE

Experience with wire rope in the initial prototype moorings meant that they were predominantly removed from the main mooring spread. Wire is only used in one place in the main moorings, as the forerunner to the front anchor. In this location there is no cyclic, low tension motion that was the root cause of the issues in the prototype moorings. The ø70mm Bridon Dyform 34LR wire rope used is a high strength, low rotation specialist rope with good bending fatigue properties and excellent resistance to crushing and abrasion. The cost metrics associated with this rope is shown in Table 9 below and include closed spelter sockets each end.

	Cost (nearest £100)	**Mass / SWL**	**Cost Metric**
70m x ø70mm Dyform 34LR wire rope	£8,300	1715kg	£4.80/kg
		445Te	£0.26/Te SWL per m

Table 9: Specialist low rotation, high strength wire rope cost metrics

3.6.2 STANDARD IWRC WIRE ROPES

More standard IWRC (independent wire rope core) wire ropes are often used for marine operations and these are also used in the yaw line. Based on the multitude of purchase orders fulfilled over the P2 development and operations programme the following cost metrics for IWRC rope can be calculated.

Cost Metric	Value
Cost / kg	£2.80/kg
Cost / Te (break load) per m length	£0.20/Te BL per m

Table 10: IWRC wire rope cost metrics

3.7 CONNECTION PLATES

The P2 mooring system uses tri-plates underneath the tether hooks to connect the vertical tether lines to both the front and rear mooring lines. This connection can be seen in the photograph below. The plates are made of high tensile steel, undergo strength proof-load tests and are supplied with the relevant material and test certificates. The cost metrics of these plates is shown in Table 11. The cost of these components per kilogram is comparable to that calculated for shackles and detailed in section 3.8.

	Cost (nearest £100)	Mass / SWL	Cost Metric
Triplates	£1,300	256kg	£5/kg
		150Te	£8.40/Te SWL

Table 11: Connection plate const metrics

Figure 7: Triplates during mooring installation (left) and specification (right)

3.8 SHACKLE CONNECTIONS

Shackles are used throughout the mooring spread to connect line sections together. Back to back shackles are used to achieve this. The majority of connections are made with 85Te to 150Te SWL D15 type D safety shackles with additional resistance to accidental release provided by drilling the locking nut and shaft and through bolting with an M10 or M12 stainless bolt and stainless nylock nut. Stainless steel split pins were also used to provide added protection.

In two locations in the mooring system it was important that the connecting shackles aligned well throughout their range of motion. In these locations bow shackles are used. The bow shackle is more prone to fatigue than the D shackle and was therefore oversized to compensate. The two locations where bow shackles were used were at the connection of the front anchor's wire forerunner and at the transition from 3" to 5$^{1}/_{8}$" chain in the front lines where there is also a backup chain connection. In failure cases which bring the backup chain into play the relative orientation of the shackle change. The relative motion is accommodated by the smaller shackles moving around the bow of the 150Te shackle. This connection can be seen in the left hand picture in Figure 8. Examples of the back to back shackle connections used to connect the anchors and chain sections together can be seen in the right hand photos.

Figure 8: Backup line connection using overrated bow shackle (left) and back to back shackle arrangement used for anchor connection and the majority of chain connection in the mooring system.

To determine a cost metric for shackle connections the purchase orders for standard mooring shackles issued throughout the P2 development and operations program have been brought together. Specialist shackles such as the wide mouth shackles used in the tow rigging during installation have been excluded from the combined analysis but cost metrics for these are included below for interest. With the exclusion of the wide mouth shackles a fairly consistent cost per kilogram emerges for a variety of shackle types, over a range of safe working loads has emerged. The standard deviation of this figure for the shackles analysed is £0.90.

Cost Metric	Value
Cost / kg	£5.40/kg
Cost / kg standard deviation	£0.90/kg

Table 12: Cost metrics for shackle connections

The metric for cost per tonne SWL is not as simple although it does appear have a linear relationship with the SWL. This increase in cost per tonne SWL as the SWL of the shackles increases as can be seen in Figure 9.

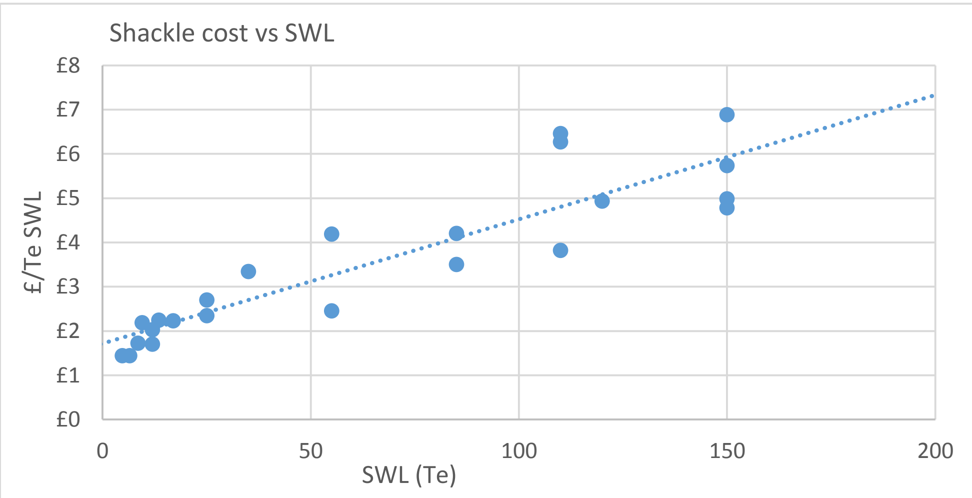


Figure 9: Increase in £/Te SWL as the safe working load of the shackle increases

3.9 ANCHORS

The Pelamis mooring system requires anchors capable of withstanding large horizontal loads but only minimal vertical loads. This functional requirement, coupled with the sea bed conditions at the EMEC test site make drag embedment anchors the most suitable type to use. Conventional high holding power drag embedment anchors were used for both the front and rear mooring lines. Stevpris Mk5 anchors were chosen and used on each of the P2 mooring spreads. Examples of these anchor types can be seen in Figure 10.

In the P2-002 mooring spread, cost considerations and the availability of smaller anchors meant that 3 smaller anchors were piggy-backed together to achieve the holding capacity required on the front mooring line. A 3Te Stevpris Mk5 anchor was used in series with 2 x 2.5Te Stevpris anchors to achieve the holding capacity required. A single 5Te Stevpris Mk5 anchor can achieve the same holding capacity and this is the cost that has been used in the example mooring infrastructure costs in section 8.

Mooring installation included the setting/embedment and proof loading of the anchors and the following estimated maximum holding capacities were achieved.

	Proof Load	**Estimated Holding Capacity**
Front Anchor(s)	~145Te	210-250Te
Rear Anchor	~85Te	120-150Te

Table 13: Holding capacity of the front and rear anchors in the P2 mooring system

Figure 10: Vryhof Stevpris Mk5 anchors as used in the P2 Pelamis mooring system

In terms of cost, as might be expected anchors have a relatively low cost per unit mass since they are relatively simple fabrications from plate material. This cost is comparable to the 'basic fabrication' cost that is detailed in the PTO cost metrics report (SEC-D-006, section 6.2). PWP were able to purchase used anchors on a couple of occasions. The costs of these anchors was reduced by approximately 25%.

	Cost per kg	**Cost per Te holding capacity (medium clay)**
Stevpris Drag Embedment Anchors	~£3/kg	£57/Te Holding Capacity

Table 14: Cost metric for drag embedment anchors

3.10 CLUMP WEIGHTS

Clump weights are only used in the secondary mooring system, or the yaw line. For the P2 machines passive yaw constraint was provided to ensure that the Pelamis machine could not yaw sufficiently to turn full circle which would have resulted in damage to the umbilical cable at the front of the machine. A single block clump weight was attached via an assisted catenary fixed length mooring line to tube 4 of the Pelamis device. The mooring line included a separate 6Te chain clump weight. The yaw line configuration is illustrated below. The costs of the different types of clump weight are shown in Table 15 thereafter.

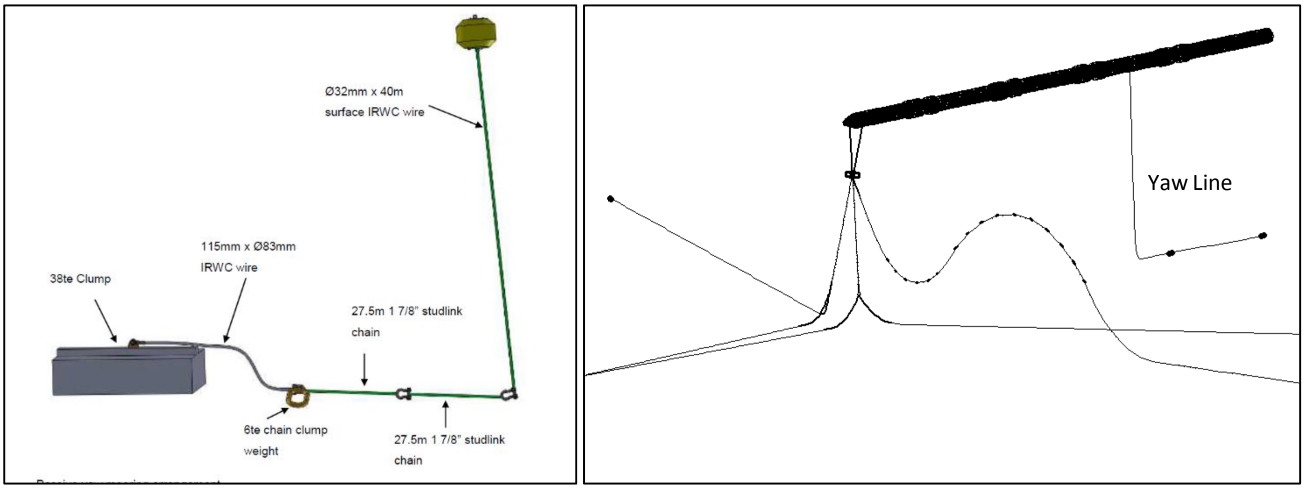


Figure 11: Yaw line configuration (left) and attachment point to the Pelamis device (right)

Clump Weight Type	Cost / Te
Block mooring clump weights	£270/Te
Chain clump weights	£330/Te

Table 15: Clump weight cost metrics

4. SUBSEA ELECTRICAL INFRASTRUCTURE

4.1 WET-MATE CONNECTORS

4.1.1 POWER WET-MATE

The preferred metric to apply to power wet-mate connectors would be £/kW, however this is not realistic given the limited available information. Additionally, the cost to terminate the cable into a mechanical assembly can vary greatly between connectors. Table 16 below is a summary of a survey carried out by PWP to investigate wet-mate power connectors suitable for use with a Pelamis WEC, their differing specifications and cost. The indicative costs are based on the basic connector assembly and do not include the cost of cable termination or additional mechanical mounting and protection requirements.

	Company A	**Company B**	**Company C**	**Company D**	**Company E**	**Company F**	**Company G**
Rated Voltage	11kV	6.6kV	11kV	8.7kV	8kV	7.2-33kV	11kV
Rated Current	250A	100A	250A	220A	220A	500A	400A
# of pins	3	4	3	3	3	3	3
Max. cycles before maintenance	>100	>100	Not specified	100	100	No details	No details
Cross Sectional Area	Not specified	>95mm^2	70mm^2	35mm^2	No details	No details	No details
Test voltage	Not specified	15kV	43.2kV	20kV	No details	No details	32kA
Cost per pair for spec above	£140k	£20k	£30k	£70k	Not quoted	unknown, project specific unit	~£220k
Information source	E-mail & datasheet, 2014	Quote & datasheet, 2012	Quote & datasheet, 2013	E-mail & datasheet, 2010	Website	2014	E-mail & datasheet, 2012

Table 16: Wet-Mate Connector Survey

The wet-mate connector used with the P2 machines was the Gisma series 80 connector. For the P3 Pelamis design PWP were investigating suitable alternatives but with a higher voltage rating. PWP had in-depth discussions with Deutsch with a view to implementing the P6-3W250 connector, a connector that was not commercially available at the time of when the P2 connection system was designed. This connector has a higher one off cost to the Gisma connector, however given it is rated to operate at 11kV a greater overall saving would be made by the reduced cost and losses in the subsea cabling. It is the costs associated with this connector that have been utilised in the future indicative mooring system costs in section 8.

PWP were able to obtain the details of the breakpoint quantities from Deutsch for which a cost reduction is applied to the 11kV wet-mate connectors, illustrated in the bar graph below. For the 250A connector (a rating that would be suitable for connecting individual machines to the circuit), a 33% reduction in cost is obtained for a 10 off quantity. This cost reduction increases to nearly 50% reduction for quantities of 100 or more.

Deutsch can also supply a connector with a higher current rating of 400A. Such a connector would be suitable for use on the interconnectors between machines and in a subsea hub such as that which would be required in a wave farm. The cost reduction for these connectors is similar percentage wise to that of the connectors with a lower current rating.

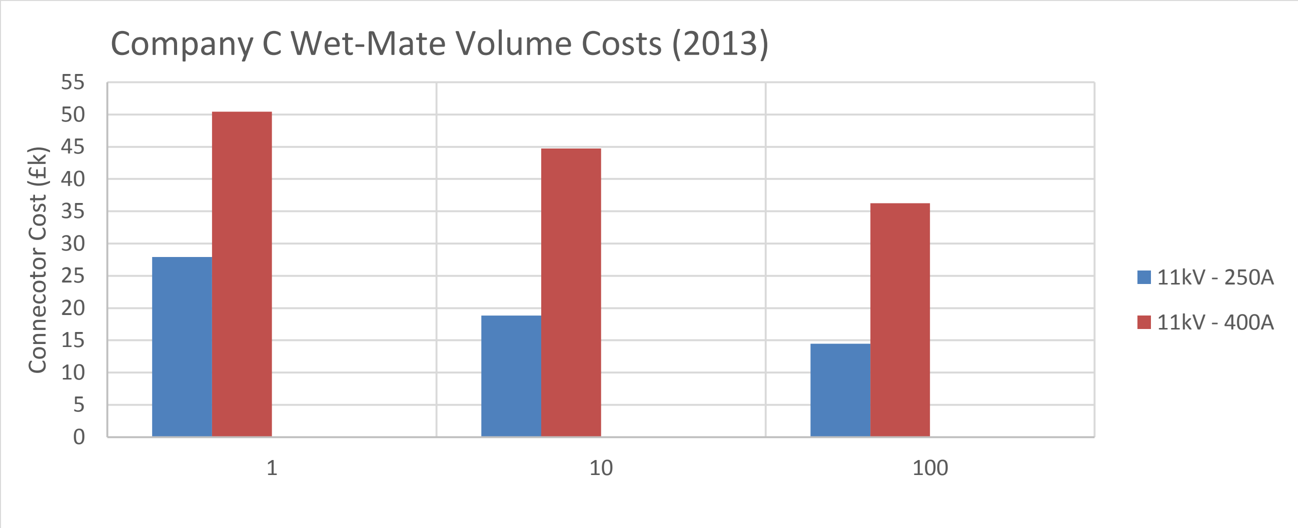


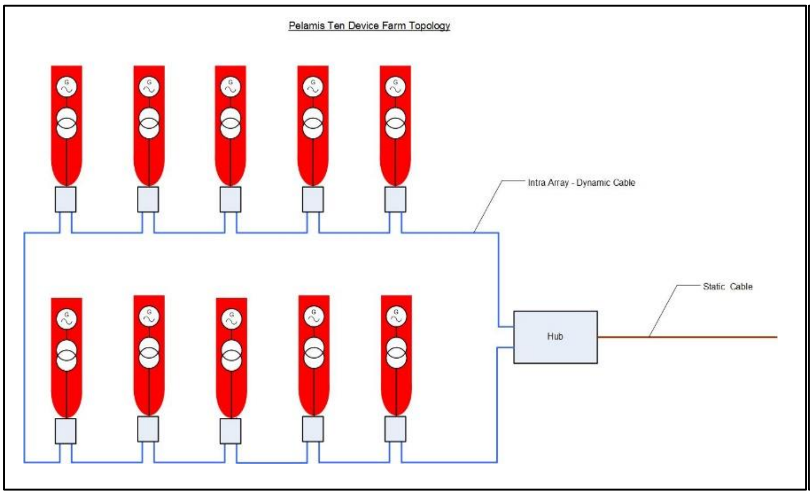
Figure 12: Power Wet-Mate Volume Costs

4.1.2 COMMUNICATION WET-MATE

It is not possible to apply a simple cost metric to a wet-mate communication connector given the communication protocol, number of channels required and medium used will vary between applications. For the Pelamis P2 machines, PWP used a copper pin Ethernet wet-mate connector manufactured by ODI to achieve the communications connection between the Pelamis and WMJB. The connector cost was £11k. Following a review of connectors from alternative suppliers no other suitable connectors were found to be available at a similar cost.

4.1.3 SUBSEA ADDITIONAL ARRAY CONNECTOR REQUIREMENTS

If the Pelamis WEC was to be deployed in a wave farm then additional connectors would be required to connect the WMJBs to the intra-array dynamic cables between the individual WECs. PWP looked in detail at how these connections might be achieved while still maintaining farm and individual machine availability and redundancy in the communications and power connections. Much of this work was still conceptual at the point of PWP administration, however, for the purposes of providing an indicative cost the subsea electrical infrastructure for a wave farm, a topology as shown in Figure 13 below has been assumed.



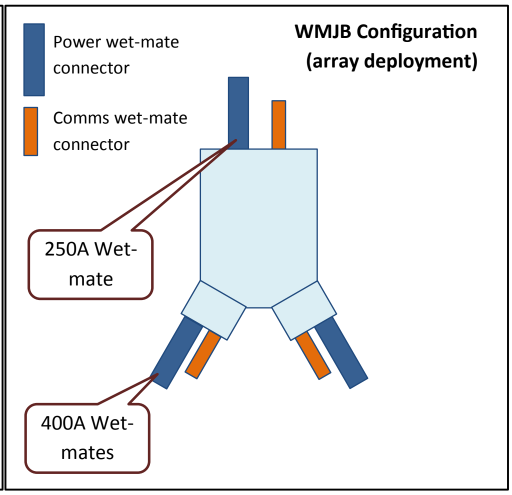


Figure 13: Farm electrical connection topology (left) and WMJB connections required (right)

The P2 WMJB only required 1 power wet-mate connector and 1 communications wet-mate connector. The dynamic umbilical was pre-terminated into the WMJB under factory conditions before deployment. It can be seen in the representation of the WMJB in Figure 13 above, however, that in a wave farm, each WMJB requires 3 power connections and 3 communications connections. It had been decided that having no pre-terminated connection was beneficial for operational and maintenance reasons. It is possible that some of the connectors at the end of the dynamic cables could be mated on the deck of an offshore vessel, therefore "dry-mate" or "deck-mate" connectors could be used as an alternative to "wet-mates". The only advantage to using a dry-mate over a wet-mate would be if it was available at a reduced cost. However, following a review of the suitable dry-mates commercially available, PWP did not find that there were any suitable dry-mates available at a lower cost. For this reason only the cost of wet-mate connectors are considered in the mooring system costs examples at the end of this document.

In terms of the communications connectors, the current connectors used in the P2 WMJBs are copper pin Ethernet connectors since a media converter can be located in the WMJB to allow the use of these lower cost connectors. It would not be possible to use Ethernet connectors for the connections at each end of the dynamic cable between devices. A suitable wet-mate fibre optic connector was identified from Deutsch at a cost of £23K for a 1 off quantity. The next price break for 35 off these connectors brought the cost down to £12k.

4.2 DYNAMIC CABLE

The subsea electrical infrastructure for the Pelamis is constructed from two types of cable, one static and the other dynamic. Figure 13 above illustrates one possible topology for a farm of Pelamis WECs. The static cable would be routed from the shore substation along the seabed to the semi-submerged array "Hub". From the hub a dynamic type cable would be used for the intra-array cabling to each Pelamis device.

The cost of a subsea cable is vulnerable to the cost of the raw material commodities copper and steel. When obtaining a quote for a cable the manufacturer will usually add a caveat that the cable cost will vary according the cost of copper at the time the order is placed. For a cable of the same rating the unit cost of a dynamic cable will be greater than for a static cable because a dynamic cable needs to be torsionally balanced. In general, a cable is specified by its rated operating voltage and cross sectional area (CSA) of the conductor. The CSA of the cable directly relates to the maximum current rating of the cable.

There is nothing special or bespoke in the design of subsea cable required for a wave farm, this type of cable is commonly used in many other established subsea applications, such as the oil and gas industry or in offshore wind farms. Cable is not supplied ex-stock and is manufactured to order, there is usually a minimum order quantity (MOQ) of 1km specified by the manufacturer. A typical cable construction will have 3 copper cores for power transmission and a multicore core FIST (Fibre In Steel Tube) for data communication. The FIST typically represents 2-3% of the total cost of the cable and there are usually 12-24 fibre optic cores within each steel tube.

It is always preferable to operate at as high an operating voltage as possible in order to minimise cable losses, cable size and cost. Factors that limit the operating voltage in the first wave farm that PWP was planning to develop were, the availability of suitably rated wet-mated connectors and prohibitive cost of using a subsea transformer for stepping up the voltage for transmission to the shore.

The basic cost metric for subsea cable is cost/m according to voltage and CSA. However, cable suppliers do not provide list price tables for all the possible variations of cables that they can manufacture. A quotation is usually provided based on the specification requirement submitted. PWP obtained static and dynamic cable costs for a 10 machine farm from three different manufacturers, these are shown in Table 17 below.

Manufacturer	11kV, 500mm² Static Cable (qty – 15000m) (£/m)	11kV, 120mm² Dynamic Cable (qty -3000m) (£/m)	Project Management Cost (£) - including dynamic analysis
Company A	£268	£210	£973,000
Company B	N/A	£147	£50,000
Company C	£416	£188	£366,000

Table 17: Farm Subsea Cable Cost

From the quotations obtained, there is clearly a significant variation in cable and project management costs. One can only assume that significant higher management costs quoted by Parker and Oceaneering is because they are not setup to manufacturing cable in such low volume. For the purposes of the example costings in section 8 an average cost of the costs above has been used and dynamic cable is assumed to cost £180/m.

The cost of the subsea cable in a 10 Pelamis farm can represent more the 25% of the mooring capital expenditure. It is therefore worthwhile thoroughly investigating any opportunity for cost saving in this area. The most simplistic approach is to rate the cable for the peak generation of all the WECs within an array. However, given the WECs only generate at full power for only a small percentage of the time this will lead to a system design with a low utilisation factor. A model could be developed to investigate the economic effects of under-rating some of the cable in order to increase utilisation.

There are a number of input parameters that need to be considered in order to derive the "best fit" cable configuration and size. One of the most significant factors to consider is the capacity factor of the WECs and analysis of time spent generating at different power levels. The power histogram shown below in Figure 14 illustrates the frequency of occurrence at different power generation levels for the P2 Pelamis.

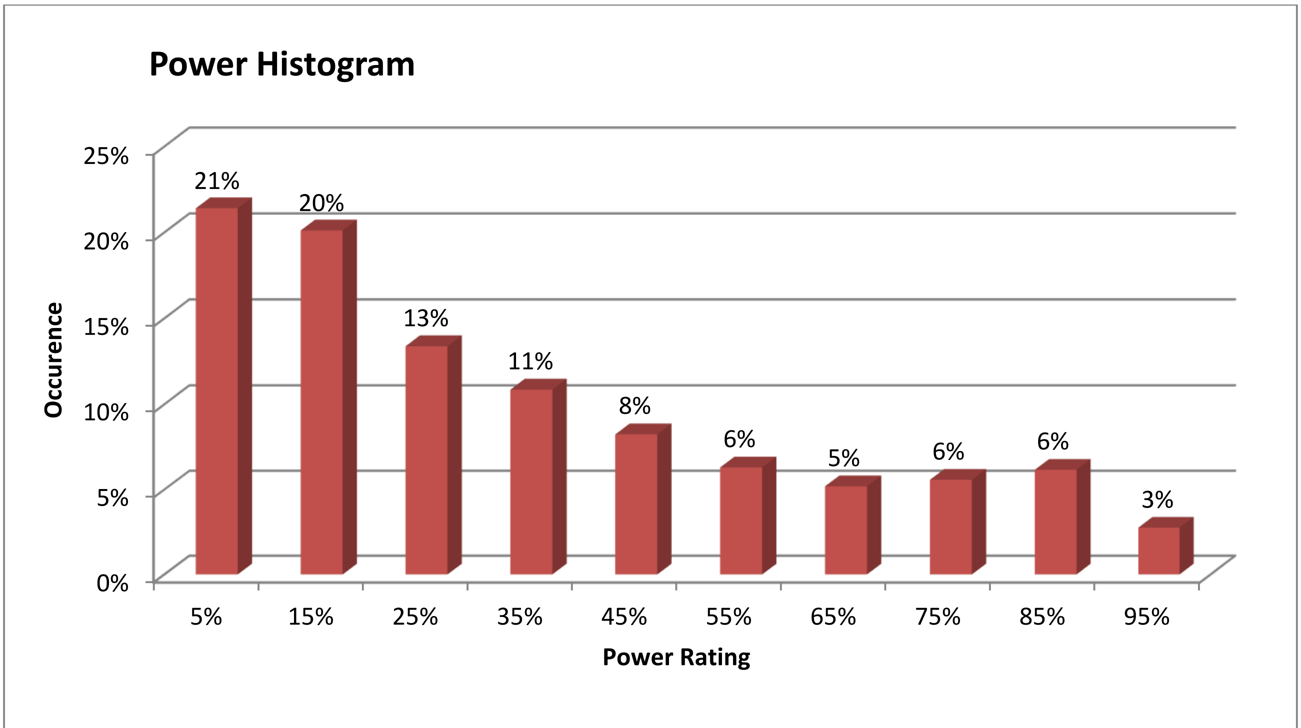


Figure 14: Power histogram for the P2 Pelamis (based on the EMEC occurrence table)

By calculating the revenue generated at each power level over the lifetime of the project it should be possible to determine the optimum inter-array and export cable capacity. The optimal cable size may require the curtailment or reduction of generation during certain periods of time.

The many other factors to be considered in order to determine the optimal cable size, rating and length of the cable, some these are:

- Farm topology - determined by redundancy required, installation methodology, mooring constraints and O&M regime.
- Seabed Temperature – Seasonal variation in the sea temperature will affect the maximum operating current of a cable. The predicted average power output of a Pelamis will also vary seasonally. We can then correlate the required ampacity against the seasonally available ampacity for different cable sizes and use this information as criteria for the selecting the optimal cable size.
- Installation Costs – the type, size and hence cost of installation vessel will vary according to the individual length of cables installed.

To conclude, there no simple cost metrics to determine the optimal subsea cable sizes for a wave farm, there are many factors to consider. In order to consider all the known factors that determine the optimal cable size, rating and configuration, a complex system model would have to be developed.

4.3 CABLE BUOYANCY, BALLAST & TOUCHDOWN CLUMP

As sown in Figure 13, machines within a row are electrically interconnected, in series to other machines within the same row via flexible umbilical “interconnectors”. A single row of machines is connected to the “hub”, and thereby the static export cable, via a dynamic umbilical downfeeder. This is illustrated in Figure 15 below. In addition to the connections shown there is also a row interconnector between the rows of machines in a farm at the opposite end to the downfeeder cable.

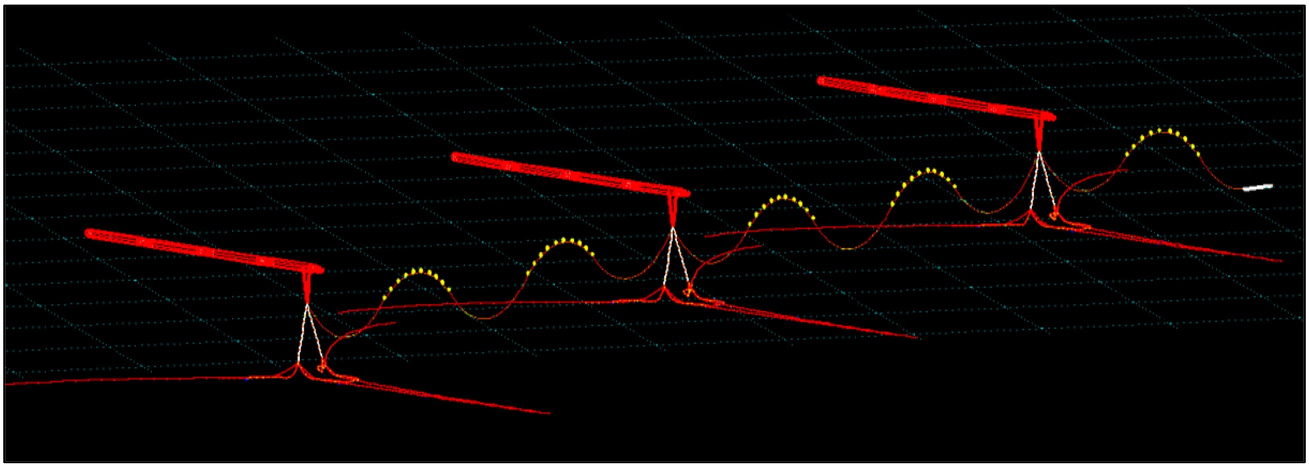


Figure 15: Example management of electrical cable between machines in the row of a farm. Slack in the cable is managed by attaching buoyancy modules to form “arches” in the cable. “Troughs” are weighted down by small floats.

Each of the interconnectors and downfeeders needs to have significant slack in the cable to allow for movement of machines relative to their individual moorings as well as one another. To achieve this, interconnectors are installed mid-water with cable buoys and weights used to form arches in the cable. Between machines and between rows, 2 cable “arches” would be installed. A single “arch” is required on the downfeeder cables. Each “arch” is supported by 15x Mobilis cable floats which provide 100kg of buoyancy each. The troughs are weighted down by 40kg ballast modules which are PWP designed.

Where the cable touches down onto the seabed, clump weights (and associated rigging) are required to maintain the cable’s location to ensure it does not get dragged across the sea bed and become damaged. The central “trough” between machines in a row will have a length of cable on the sea bed with a clump weight at each end. A similar arrangement would occur in the interconnector between rows of machines where again, the central trough would have a length of cable on the sea bed and 2 clump weights at the touchdown points. Only a single clump weight is required on the down-feeder cables before the cable is routed over the sea bed to the farm hub.

The cost of the buoyancy, ballast and cable touchdown clump weights is shown in Table 18.

Cable Management Costs	Cost each
Cable buoyancy (100kg)	£600
Cable ballast (40kg)	£300
Cable touchdown clump weight & rigging	£8,000

Table 18: Cable management Costs

4.4 BEND STIFFENERS

Bend stiffeners are required to limit bending stresses, curvature and minimum bend radius on the dynamic cable during the project life and to prevent cable damage during installation. Two types of bend stiffener were proposed for use in the Pelamis mooring system, static bend stiffeners and dynamic bend stiffeners. Dynamic bend stiffeners are required at the cable exit point from the WMJB and at cable touch down points on the sea bed. Static bed stiffeners are also required at the cable touch down points on the sea bed on the static part of the cable between touchdown clump weights. PWP worked with Trelleborg to design an appropriately sized dynamic bend stiffener for the P2 mooring system (visible in the photographs below). The costs for these units are shown in Table 19 thereafter.

In the P2 mooring configuration dynamic bend stiffeners were used on both sides of the cable splice rather than static bend stiffeners. This was done due to time and engineering constraints given a dynamic bend stiffener met all the requirements. However, in future projects, it was anticipated that static bend stiffeners would be used where possible since they are slightly cheaper. Their cost has been estimated in the table below.

Figure 16: Dynamic bend stiffeners were used at the cable exit point from the TLA (left) and during the cable installation process (right)

Cable Management Costs	Cost each
Dynamic Bend Stiffener	£12,000
Static Bend Stiffener	£10,000

Table 19: Cable Management Costs

5. MOORINGS INSTALLATION INDICITIVE COST

The CAPEX costs of the moorings only really tells half the story. The costs associated with the installation of the moorings is obviously an important consideration for the economics of any wave farm. However, installation costs are also much harder to estimate given the uncertainties surrounding weather and vessel costs.

The table below gives indicative costs for mooring spread installation at EMEC for a single Pelamis device. It has been assumed that multicat vessels are used where possible. However, it is not possible to complete the entire moorings installation with multicat vessels. An anchor handling vessel is required for installation of the yaw clump weights and dynamic cable.

The costs shown are estimates only based on experience to date but are arrived at using sound engineering judgement. The expenditure in each area has also been represented as a percentage of overall mooring installation costs in the pie chart in Figure 17. As expected, the vessel hire costs dominate and account for nearly 50% of the overall installation cost.

The following assumptions were used when estimating the costs in Table 20:

- Multicat hire costs are £4000/day
- Multicat fuel costs are £1000/day
- Anchor Handler Tug hire costs are £20,000/day
- Anchor Handler Fuel costs are £9,000/day
- Harbour Tug costs are £6,000/day
- ROV hire costs £2000/day
- Positioning spread costs are £1,500/day

Description		**Approximate Cost (£k)**
Temporary Installation Equipment		£60k
e.g.	Surface buoys	
	Surface wire	
	Chain	
	Misc. shackles & connectors	
	Misc fasteners & split pins	
	ROV	
Logistics		£40k
e.g.	Delivery of anchors, chain, clump weights, cables etc	
	Delivery of bespoke assemblies from Leith	
	Storage of mooring equipment	
	Loadout cranes	
Services		£20k
e.g.	Seabed surveys	
	Geotechnical interpretation	
	Cable handling equipment & personnel	
Consumables		£2k
Vessel Hire		£330k
	Multicat mobilisation & demobilisation (5 days)	
	Multicat for primary mooring installation (14 days)	
	Harbour Tug for anchor embedment (10 days)	

	Anchor Handler Tug mobilisation & demobilisation (2 days)	
	Anchor Handler Tug for yaw mooring installation (1 days)	
	Anchor Handler Tug for cable work (2 days)	
	Multicat for TLA install (4 days)	
	ROV hire (20 days)	
	Positioning Spread (20 days)	
Vessel Consumables (Fuel)78		£70k
Vessel Ancillary Costs		£15k
e.g.	Harbour dues	
	Pilotage	
Personnel Costs		£150k
e.g.	Project Management	
	Offshore operations crew (developer's)	
	Installation engineering	
	Design & verification	
	Travel	
	Expenses	
10% contingency of relevant costs (vessel hire periods, fuel, offshore personnel etc)		£43k
25% contingency of relevant costs (vessel hire periods, fuel, offshore personnel etc)		£108k
50% contingency of relevant costs (vessel hire periods, fuel, offshore personnel etc)		£216k
MOORING INSTALLATION TOTAL (No Contingency)		**£687k**
	+10% contingency of relevant costs	£730k
	+25% contingency of relevant costs	£795k
	+50% contingency of relevant costs	£903k

Table 20: Estimated moorings installation costs for a single Pelamis mooring system using drag embedment anchors. It has been assumed that multicat type vessels are used where possible.

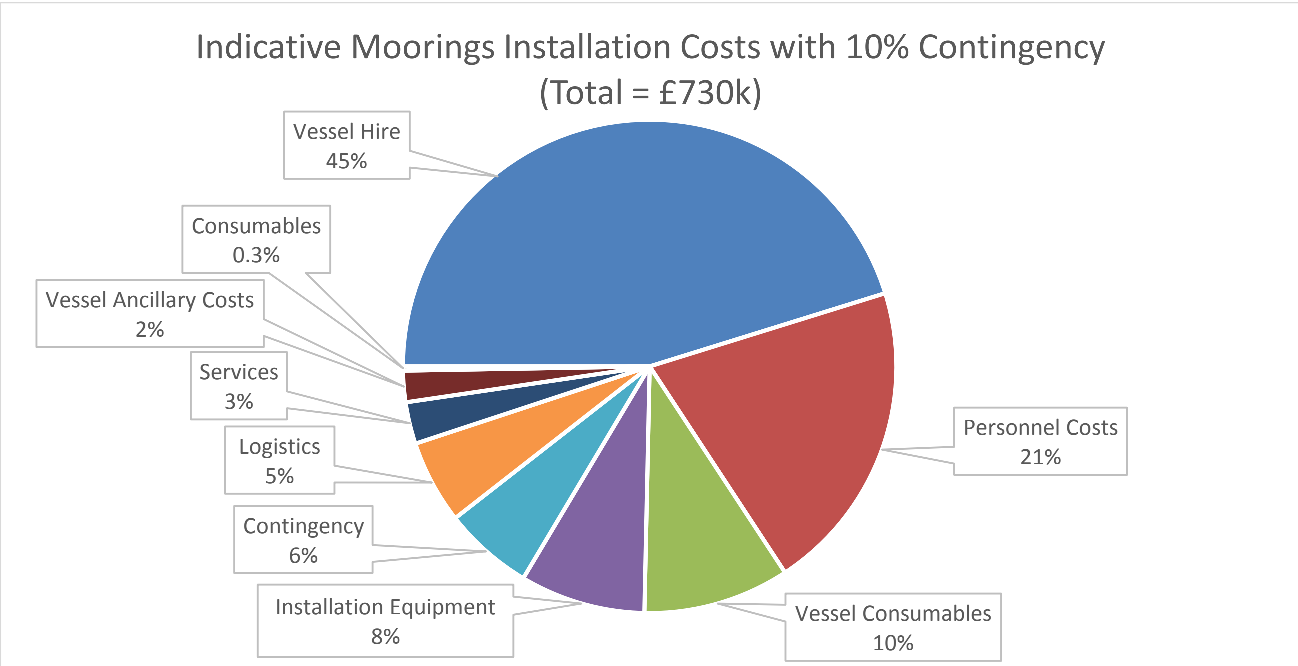


Figure 17: Breakdown of estimated mooring installation costs

6. MACHINE INSTALLATION INDICITIVE COSTS

The following table provides a breakdown of the typical costs PWP incurred for Pelamis intervention operations with the P2 machines at EMEC. These costs do not include any costs associated with vessel or crew mobilisation. They would obviously also be highly dependent on the length of tow and size of vessel required for the tow. For the P2 machines at EMEC, a 30Te bollard pull vessel was required, the tow was approximately 25km long (3hours duration at an average speed of 4-5knots), and the main installation vessel was on long-term hire which reduces costs.

These costs were provided in the deliverable 1 report but are provided again here for completeness of this deliverable.

	Plant/Requirements	**Approximate Cost**
Site/Machine Preparation		
	Vessel, crew & inspection class ROV	£3,500
	Quayside personnel / equipment prep.	£1,000
Machine Installation		
	Pilotage	£650
	Rear vessel charter (inc. fuel)	£3,800
	Installation Vessel (inc. fuel)	£4,200
	PWP Personnel (inc. mob costs)	£2,500
	SAEP and onshore personnel	£500
Machine Installation Total		**£16,150**
Machine Recovery		
	SAEP and onshore personnel	£500
	Pilotage	£650
	Recovery Vessel (inc. fuel)	£4,000
	PWP Personnel (inc. mob costs)	£2,000
Machine Removal Total		**£7,150**
TOTAL INSTALLATION/REMOVAL CYCLE COSTS		**£23,300**

Table 21: Indicative costs associated with a P2 installation and removal cycle

7. MACHINE LOCATED RAIPD CONNECTION COMPONENTS

Although the focus of this report is the permanently installed moorings components, the rapid connection and disconnection system would not work without the associated machine mounted components and systems. The following section gives a brief overview of the costs related to these.

7.1 MECHANICAL LATCH COMPONENTS

The latch arms, thrust washer, bearings and pins that are located at the yoke end cost a total of ~£5000. The latch arms were made from S355 steel and were blasted, primed and painted with marine grade paint. The thrust washers and pins were made from 316 stainless steel (pickled and passivated) and the bearing material was Orkot. No cost for the yoke end fabrication onto which these components are mounted has been provided here since the cost of this would be so highly dependent on the integration of these parts into a larger structure and the design of the larger structure itself. Photographs of the latch arms in place on the yoke end structure are included below for reference.

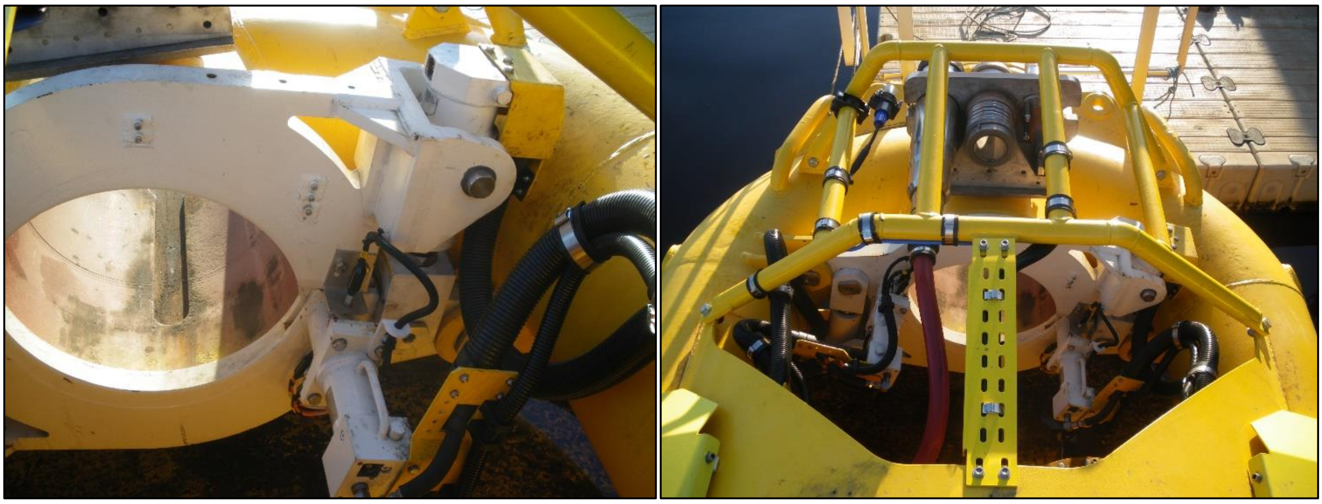


Figure 18: P2-002 yoke end with latch components installed

7.2 HYDRAULIC LATCH COMPONENTS

The following table summarises the costs associated with the hydraulic components of the latch system. No costs for the hydraulic hoses and hard pipes have been included since the lengths of these are totally dependent on the routing and separation of the components. The P2 costs are therefore not indicative of future costs where routing would have changed significantly.

Hydraulic Latch Component Costs	Quantity	Cost each
Latch Rams	2	£3,000
Locking Rams	2	£2,300
Latch Manifold	1	£2,500
Latch Power Pack (excluding manifold)	1	£4,000
Accumulator & Safety Block	2	£1,500
TOTAL		**£18,600**

Table 22: P2 latch hydraulic components costs

7.3 WET MATE CARRIAGE

The wet mate carriage (WMC) it attached to the yoke end and is the assembly onto which the wet mate connectors are mounted. The plate on which the connectors are bolted is compliant with respect to the yoke structure to enable accurate alignment of the wet mate connectors to be achieved. The main alignment spike on the WMJB is pulled into the central tube on the WMC to achieve the required accurate alignment. A secondary spike ensures the rotational alignment is correct.

The WMC is made out of 304 stainless steel and consists of numerous machined components that were professionally pickled and passivated during manufacture. The total cost of these components, including the compliant mounts and fasteners was ~£2,600. The total mass of the unit was approximately 40kg. The assembly can be seen in the photographs below.

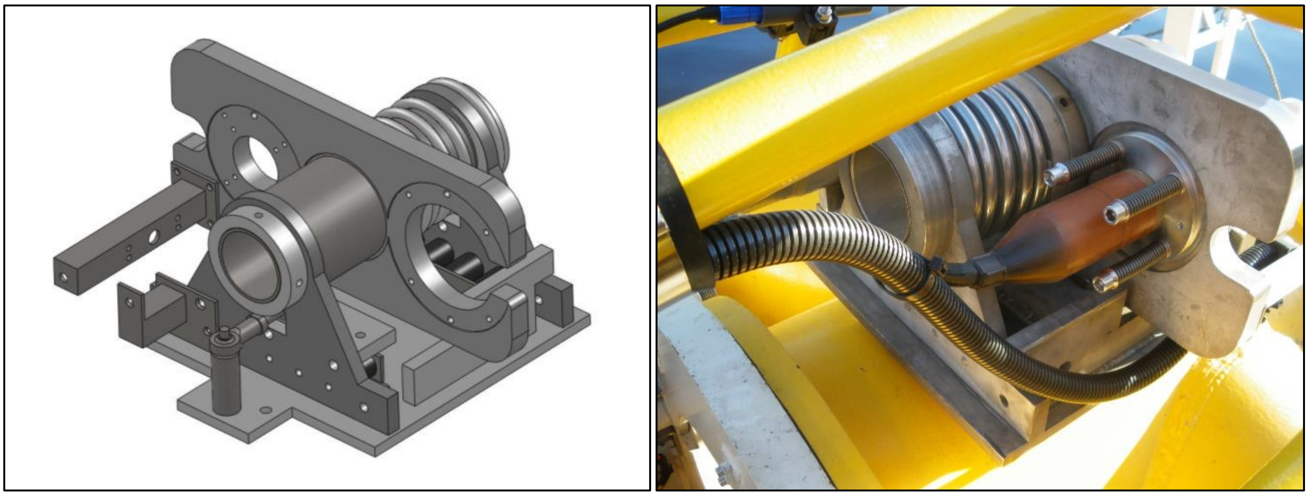


Figure 19: Wet mate carriage 3D CAD model (left) and installed on P2-002 yoke end (right)

7.4 YOKE END CAMERAS

The yoke end cameras that were used by PWP to give control personnel visual feedback of the latching process were Bowtech acrylic colour dive-cams were rated to 100m water depth. They each cost ~£650 and the 35m long sealed cable assembly that is routed up the yoke into the video servers in the nose of the Pelamis cost an additional £250.

Figure 20: Bowtech Dive-cam used by PWP to give visual feedback of the latching process. These were installed on the protection frame on the end of the yoke (right).

8. EXAMPLE MOORING & CONNECTION SYSTEMS

The Pelamis mooring system is diagrammatically represented in Figure 21 below. The tables underneath this provide specifications for the P2 mooring components and the connections between them. This section of the report is designed to provide worked examples of the full costs for indicative mooring systems and the associated electrical infrastructure. Three example system have been considered.

1. Single device, 50m water depth, 6.6kV electrical connection, passive yaw system (i.e. the P2 system)
2. Single device, 70m water depth, 11kV electrical connection, active yaw system (i.e. indicative of a single P3 mooring)
3. 10 machine wave farm, 130m water depth, 11kV electrical connection in a wave farm infrastructure, active yaw system (i.e. indicative of a wave farm P3 mooring)

In the costed examples the moorings system is broken into four sections, the seabed primary mooring components (up to the tether hook disconnection point), the tether components (those items that run vertically through the water column), the secondary mooring components, and the electrical infrastructure (including the WMJB and cable management systems). It is important to understand how the components in each section would be altered to suit different site or electrical characteristics or to allow a farm of machines to be deployed. This is specifically discussed in the sections 8.1.1 to 8.1.4 that follow. Any assumptions made in the example costing tables are also discussed here or as a footnote to the tables themselves.

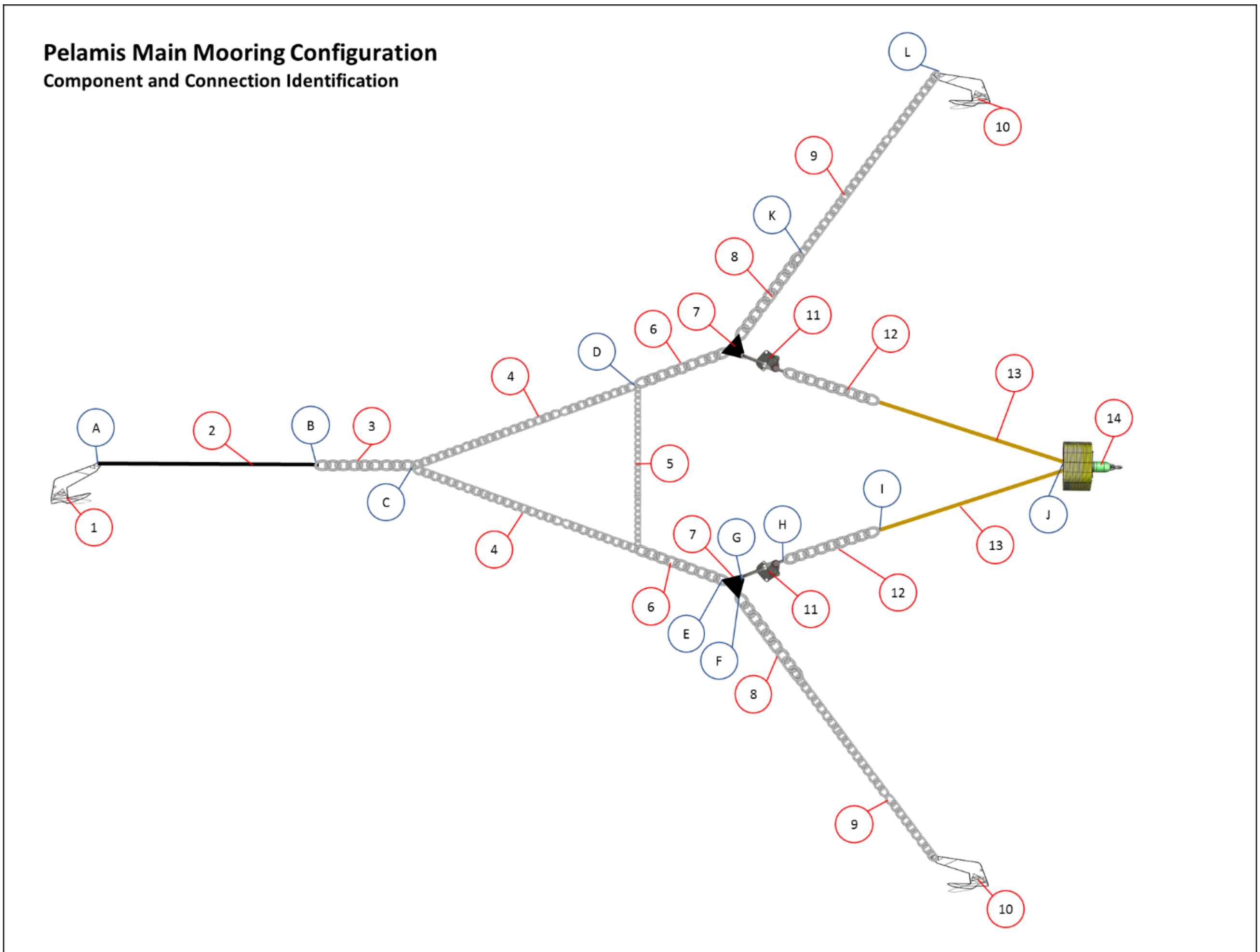


Figure 21: Pelamis main mooring components and identification. The specification of individual components (numbered in red) and connections (numbered in blue) are provided in Table 23 and Table 24 respectively.

Main Mooring System Components				
Description		P2 Embodiment		
		Quantity	Description/Specification	Length/mass/capacity
1	Front Anchor	1	Stevpris Mk5 Anchor	5Te Anchor
2	Front Anchor Forerunner	1	ø70mm Dyform 34LR wire rope	70m
3	Front Anchor Heavy Chain	1	5 3/8"(137mm) SLAC	21m
4	Front Anchor Lines	2	3" (76mm) SLAC	100m
5	Backup Line	1	3" (76mm) SLAC	21m
6	Front Anchor Heavy Line	2	5 3/8"(137mm) SLAC	17m
7	Triplate	2	TR1 Triplate	150Te SWL
8	Rear Anchor Heavy Chain	2	5 3/8"(137mm) SLAC	12m
9	Rear Anchor Line	2	3" (76mm) SLAC	190m
10	Rear Anchor	2	Stevpris Mk5 Anchor	3Te Anchor
11	Tether Hook & Masterlink	2	Tether Hook Fabrication	N/A
12	Tether Chain Section	2	3" (76mm) SLAC	13.5m
13	Synthetic Tether	2	ø125mm Gama 98 rope	18m

Table 23: P2 Main mooring system components and specifications

Main Mooring System Connections		
	Specification	Quantity
A	120Te SWL D Shackles (back to back)	2
B	150Te SWL Bow Safety Shackle (back to back)	2
C	150Te SWL Bow Safety Shackle 120Te SWL D Shackles	1 2
D	85Te SLW Bow Safety Shakle 150 Te SWL Bow Safety Shackle 120Te SWL D shackle	2 2 2
E	120Te SWL D Shackles (back to back)	4
F	120Te SWL D Shackles (back to back)	4
G	150Te SWL D Shackle	2
H	150Te SWL D Shackles (back to back)	4
I	150Te SWL D Shackles (back to back)	4
J	150Te SWL D Shackles (back to back)	4
K	120Te SWL D Shackles (back to back)	4
L	120Te SWL D Shackles (back to back)	4

Table 24: P2 Main mooring system connections, specifications and quantities

8.1 ALTERATIONS FOR DIFFERENT MOORING SPECIFICATIONS

8.1.1 PELAMIS MACHINE CONFIGURATION

The type of device attached to the mooring can obviously have a direct impact on the configuration of the mooring system since it can change the mooring loads that need to be designed for. Dynamic analysis showed the peak ULS combined tether load in the P2 mooring system was ~170Te. This was based on the machine being moored in a 50m water depth.

The proposed P3 Pelamis device was considerably larger than the P2 machine. It was anticipated that the P3 device would have 6 single degree of freedom joints and a larger 7.5m x 5.5m cross section. It might be expected that the large increase in machine volume had a correspondingly large increase in mooring loads. However, this is not necessarily the case. The 3m diameter prototype device had similar ULS loads but was much smaller than the 4m diameter P2s. Although far from complete, based on the analysis completed up to the date of PWP administration, it was believed that the P3 mooring system would have similar ULS load cases to the P2 mooring system if it was installed in the planned 70m water depth. Therefore, the strength characteristics of the individual components would not be altered and chain sizes and tether diameters can remain the same as those used in the P2 mooring system. The assumption that the ULS load cases would remain the same for the P2 and P3 mooring spreads has been used in section 8.4 to estimate indicative P3 mooring costs.

The other significant difference between the P2 and P3 machines is the yoke. The P2 machines had a 15m yoke that hung off the nose tube. The yoke provided a moment arm out from the machine which enabled roll restraint to be imparted to the machine from the mooring system. The TLA was winched up and latched into to yoke end during the installation process. Due to the additional roll stability inherent in the P3 shape a yoke structure was no longer required. Designs for the P3 latching system had not been completed at the time of PWP administration, however, it was anticipated that it would be winched up fully into the nose tube rather than into a yoke structure. Inevitably, this alteration would change the TLA design and may have changed the costs associated with it but with no finalised designs the costs have been assumed to be consistent with the P2 with only slight changes in buoyancy allowances to account for different tether lengths or WMJB masses.

8.1.2 WATER DEPTH INCREASES

The only section of the mooring system that changes as water depth increases is the tether section. The length of the tether (chain + synthetic rope) is a function of the depth at which the TLA is designed to sit when the Pelamis is not attached to the moorings. In the P2 mooring system the TLA sat at approximately 25m water depth when not connected to the machine. The tether length was set to 18m to ensure the tethers did not touch the seabed during this time which could have resulted in tether damage. The buoyancy of the TLA supported them, the tether hooks, and approximately the first 5m of mooring chain below them.

In deeper water, support of the hooks and the 1st 5m of chain is still required. For the P3 machine, however, the TLA can sit hit higher up in the water column when not connected since there is no yoke structure. It has been assumed for the P3 mooring system costed examples that the TLA sits 15-20m below the waterline to ensure it still remains below any aggressive wave action when not connected to the machine. The tethers have been adjusted in length for the water depth to achieve this.

8.1.3 YAW SYSTEM CHANGES

The P2 mooring spread included a passive yaw system with a single mooring line connected to a clump weight. It had been shown that the introduction of an active yaw system would lead to significant performance improvements. To achieve this, the yaw design was altered to include a continuous length of chain, anchored to the sea bed at each end, and connected to tube 4 of the Pelamis. A gypsy wheel can then be used to run the Pelamis in either direction along the chain to achieve the desired heading. The image below illustrates this concept. The active yaw moorings would no longer contain any wire rope but would be a chain assembly in their entirety.

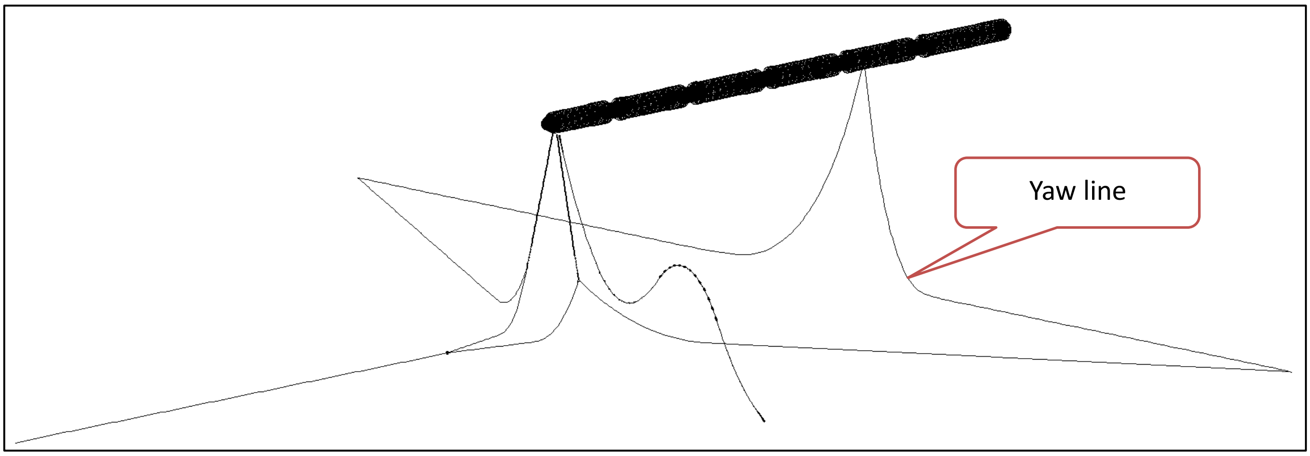


Figure 22: Proposed yaw line arrangement for the P3 machine

In Figure 22 above the yaw line is shown connected into the rear anchors. This was considered to reduce anchor costs but was not ultimately the configuration chosen since the drag embedment anchors currently used would have to be changed for gravity anchors. Instead, it has been assumed, as per the latest designs prior to PWP administration, that the yaw line is connected to its own separate clump weights (and associated chain clump weights) at either end.

Numerous ideas for connecting the chain into a drive system in the Pelamis structure had been explored. This was a work in progress at the time of PWP administration and no definite decisions had been made. In all likelihood a structure similar to the TLA would be required. Both structural and buoyancy elements based on TLA cost metrics with masses/volumes estimated based on sound engineering judgement have been allowed for in the example costings.

8.1.4 ARRAY CONSIDERATIONS

In order to estimate mooring costs for a 10 machine wave farm a number of assumptions have been made relating to the array dimensions, electrical infrastructure and possible array configurations. The costed example of a mooring spread for the 10 machine array shown in section 8.4 is based on the following assumptions:

- There is no sharing of anchors between machine mooring spreads, i.e. each mooring spread has its own drag embedment anchors. Anchor sharing has the potential to reduce costs but would involve the use of gravity anchors (clump weights) to enable tension to be applied in differing directions. The cost of these at the sizes required and with the associated steel frames and multiple attachment points needed is not part of this cost metrics report and therefore has not been included. Additionally, PWP investigations into array anchoring costs using different anchoring technology indicated that gravity anchors would not actually save money despite the anchor sharing capability.
- There is an assumed 500m spacing between machines in a row and 400m spacing between rows. Dynamic cable lengths are based on these dimensions.
- The array layout is assumed to be two rows of 5 machines as shown in Figure 13.
- The electrical infrastructure is assumed to be a ring formation with switchgear in each machine and offline switches in the wet-mate junction boxes to provide redundancy and means of isolation of parts of the array.

8.2 P2 MOORING COSTS (50M WATER DEPTH, 6.6KV, PASSIVE YAW)

Sea Bed Primary Moorings Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
Anchors	11	Te (1 x 5Te + 2 x 3Te)	£3.00	£/kg	£33,000
Chain	120	Te	£0.95	£/kg	£114,000
Wire (high strength, low rotation)	1715	kg (70m of ø70mm wire rope)	£4.80	£/kg	£8,232
Tri-plates	512	kg (2 x 150Te SWL triplates)	£5.00	£/kg	£2,560
Shackles	4684	kg	£5.40	£/kg	£25,294
Sea Bed Primary Moorings Total *(nearest £1000)*					**£183,000**
Tether Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
TLA Structure	1350	kg	£11.00	£/kg	£14,850
TLA Buoyancy	5.2	m^3	£4,000	£/m3	£20,800
TLA Ancillary items	1	Units	£4,500	Unit Cost	£4,500
Tethers (rope cost)	36	m (2 x 18m tethers)	£80	£/m	£2,880
Tethers (unit cost)	2	Units	£4,000	£	£8,000
Tether Shackle Connections	1920	kg (12 x 150Te SWL D Shackles)	£5.00	£/kg	£9,600
Tether Chain	2430	kg (2 off 9m of 76mm SLAC)	£0.95	£/kg	£2,309
Tether Hooks & Masterlink	2	Unit	£9,420	Unit cost	£18,840
Tether Components Total *(nearest £1000)*					**£82,000**
Secondary Moorings Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
Clump Weight	36	Te	£270	£/Te	£9,720
Chain Clump Weight	6	Te	£330	£/Te	£1,980
IWRC wire	4078	kg (115m of ø83mm IWRC wire + 40m of ø32mm IWRC wire)	£2.80	£/kg	£11,418
Secondary Moorings Total *(nearest £1000)*					**£23,000**
SubSea Electrical Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
WMJB Fabrication	470	kg	25	£/kg	£11,750
WMJB Internals	1	Unit	£6,000	Unit Cost	£6,000
Power Wet-mate connectors	1	Unit (Gisma 6.6kV connector)	£20,000	Unit Cost	£20,000
Comms Wet-mate connectors (copper)	1	Unit (ODI Ethernet connector)	£11,000	Unit Cost	£11,000
Dynamic Cable Penetrators	1	Unit (penetrator into WMJB)	£12,000	Unit Cost	£12,000
Dynamic Cable	1000	m	£180	£/m	£180,000
WMJB Bend Stiffeners	1	Unit	£12,000	Unit Cost	£12,000
Touchdown Bend stiffeners (static)	1	Unit	£10,000	Unit Cost	£10,000
Touchdown Bend stiffeners (dynamic)	1	Unit	£12,000	Unit Cost	£12,000
Cable buoyancy	10	Unit	£600	Unit Cost	£6,000
Cable Ballast	6	Unit	£300	Unit Cost	£1,800
Touchdown clump & rigging	1	Unit	£8,000	Unit Cost	£8,000
Sub Sea Electrical Components Total *(nearest £1000)*					**£291,000**
Grand Total					**£579,000**

Table 25: Indicative mooring spread costs based on the P2 mooring infrastructure

8.4 INDICATIVE P3 MOORING COSTS (70M WATER DEPTH, 11KV, ACTIVE YAW)

Sea Bed Primary Moorings Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
Anchors [1]	16	Te (1 x 6Te + 2 x 5Te)	£3.00	£/kg	£48,000
Chain	120	Te	£0.95	£/kg	£114,000
Wire (high strength, low rotation)	1715	kg (70m of ø70mm wire rope)	£4.80	£/kg	£8,232
Tri-plates	512	kg (2 x 150Te SWL triplates)	£5.00	£/kg	£2,560
Shackles [2]	5000	kg	£5.40	£/kg	£27,000
Sea Bed Primary Moorings Total *(nearest £1000)*					**£200,000**
Tether Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
TLA Structure	13500	kg	£11.00	£/kg	£14,850
TLA Buoyancy	5.5	m^3	£4,000	£/m3	£22,000
TLA Ancillary items	1	Units	£4,500	Unit Cost	£4,500
Tethers (rope cost)	90	m (2 x 45m tethers)	£80	£/m	£7,200
Tethers (unit cost)	2	Units	£4,000	£	£8,000
Tether Shackle Connections	1920	kg (12 x 150Te SWL D Shackles)	£5.00	£/kg	£9,600
Tether Chain	2430	kg (2 off 9m of 76mm SLAC)	£0.95	£/kg	£2,309
Tether Hooks & Masterlink	2	Unit	£9,420	Unit cost	£18,840
Active Yaw "TLA" Structure [3]	1000	kg	£11.00	£/kg	£11,000
Active Yaw "TLA" Buoyancy [4]	4	m^3	£4,000	£/m^3	£16,000
Tether Components Total *(nearest £1000)*					**£114,000**
Secondary Moorings Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
Clump Weight [5]	120	Te (2 x 60Te Clump weights)	£270	£/Te	£32,400
Chain Clump Weight [5]	20	Te (2 x 10Te chain clumps)	£330	£/Te	£6,600
Chain [5]	30	Te	£0.95	£/kg	£27,600
Secondary Moorings Total *(nearest £1000)*					**£67,000**
SubSea Electrical Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
WMJB Fabrication	470	kg	25	£/kg	£11,750
WMJB Internals	1	Unit	£6,000	Unit Cost	£6,000
Power Wet-mate connectors	1	Unit (Deutch 11kV connector)	£30,000	Unit Cost	£30,000
Comms Wet-mate connectors (copper)	1	Unit (ODI Ethernet connector)	£11,000	Unit Cost	£11,000
Dynamic Cable Penetrators	1	Unit	£12,000	Unit Cost	£12,000
Dynamic Cable	1000	m	£180	£/m	£180,000
WMJB Bend Stiffeners	1	Unit	£12,000	Unit Cost	£12,000
Touchdown Bend stiffeners (static)	1	Unit	£10,000	Unit Cost	£10,000
Touchdown Bend stiffeners (dynamic)	1	Unit	£12,000	Unit Cost	£12,000
Cable buoyancy [6]	15	Units	£600	Unit Cost	£9,000
Cable Ballast [6]	9	Units	£300	Unit Cost	£2,700
Touchdown clump & rigging	1	Unit	£8,000	Unit Cost	£8,000
Sub Sea Electrical Components Total *(nearest £1000)*					**£304,000**
Grand Total *(nearest £1000)*					**£685,000**

[1] Slight increase in anchor sizes to account for potentially slightly different sea bed composition
[2] Increase in shackle mass due to slightly larger anchors and introduction of chain based yaw system
[3] Estimated mass for active yaw TLA style component
[4] Estimated buoyancy required for active yaw TLA style component
[5] Larger clump weights required for active yaw system. £0Te of chain now included in place of IWRC wire
[6] Cable buoyancy and ballast requirements increased due to increased water depth

Table 26: Indicative mooring spread costs based on proposed P3 mooring infrastructure

8.5 INDICATIVE WAVE FARM MOORING COSTS (130M WATER DEPTH, 11KV, ACTIVE YAW)

Sea Bed Primary Moorings Components					
System Component	**Description**		**Cost / Cost Metric**		**Total (£k)**
Anchors	160	Te (10 off 1 x 6Te + 2 x 5Te)	£3.00	£/kg	£480k
Chain	1200	Te (10 off 120Te)	£0.95	£/kg	£1,140k
Wire (high strength, low rotation)	17150	kg (10 off 70m x ø70m)	£4.80	£/kg	£82k
Tri-plates	5120	Kg (10 off 150Te SWL triplates)	£5.00	£/kg	£26k
Shackles	50	Te (5Te per mooring)	£5.40	£/kg	£270k
Sea Bed Primary Moorings Total *(nearest £1000)*					**£1,998k**
Tether Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
TLA Structure	13.5	Te (1.35Te per TLA)	£11.00	£/kg	£149,000
TLA Buoyancy [1]	70	m^3 ($7m^3$ per TLA)	£4,000	£/m^3	£280,000
TLA Ancillary items	10	Units (1 per TLA)	£4,500	Unit Cost	£45,000
Tethers (rope cost)	2100	m (2 x 100m tethers per TLA)	£80	£/m	£168,000
Tethers (unit cost)	20	Units (2 per TLA)	£4,000	£	£80,000
Tether Shackle Connections	19.2	Te (1.92Te Per TLA)	£5.00	£/kg	£96,000
Tether Chain	40.5	Te (4.05Te per TLA)	£0.95	£/kg	£38,000
Tether Hooks & Masterlink	20	Units (2 units per TLA)	£9,420	Unit cost	£188,000
Active Yaw Structure	10	Te (1Te per Active Yaw "TLA")	£11.00	£/kg	£110,000
Active Yaw Buoyancy	40	m^3 ($4m^3$ per Active Yaw "TLA")	£4,000	£/m^3	£160,000
Tether Components Total *(nearest £1000)*					**£1,314,000**
Secondary Moorings Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
Clump Weight	1200	Te (2*60Te per mooring)	£270	£/Te	£324,000
Chain Clump Weight	200	Te (2*10Te per mooring)	£330	£/Te	£66,000
Chain	300	Te (30Te per mooring)	£0.95	£/kg	£285,000
Secondary Moorings Total *(nearest £1000)*					**£675,000**
SubSea Electrical Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
WMJB Fabrication [2]	7500	kg (750kg per WMJB)	25	£/kg	£188,000
WMJB Internals [2]	20	Units - 2 per WMJB	£6,000	Unit Cost	£120,000
Power Wet-mate connectors (250A)	10	Units (1 per WMJB)	£19,000	Unit Cost	£190,000
Power Wet-mate connectors (400A)	22	Units (2 per WMJB + 2 for hub)	£45,000	Unit Cost	£900,000
Comms Wet-mate connectors (copper)	10	Units (1*Ethernet per WMJB)	£11,000	Unit Cost	£110,000
Comms Wet-mate connectors (F/O)	22	Units (2 per WMJB + 2 for hub)	£23,000	Unit Cost	£460,000
Dynamic Cable Penetrators [3]	22	Units (2 per WMJB + 2 for Hub)	£6000	Unit Cost	£120,000
Dynamic Cable [4]	8600	m	£180	£/m	£1,548,000
WMJB Bend Stiffeners	20	Units (2 per WMJB)	£12,000	Unit Cost	£240,000
Touchdown Bend stiffeners (static) [5]	20	Units	£10,000	Unit Cost	£200,000
Touchdown Bend stiffeners (dyn.) [5]	20	Units	£12,000	Unit Cost	£240,000
Cable buoyancy [6]	930	Units	£600	Unit Cost	£558,000
Cable Ballast	180	Units	£300	Unit Cost	£54,000
Touchdown clump & rigging	20	Units	£8,000	Unit Cost	£160,000
Sub Sea Electrical Components Total *(nearest £1000)*					**£5,068,000**
Grand Total *(nearest £1000)*					**£9,055,000**
Average per mooring *(nearest £1000)*					**£906,000**

[1] Increase in TLA buoyancy to account for extra weight of WMJB and additional cable connections
[2] Two WMJB cable connection required therefore WMJB mass increased by 60% and internals doubled
[3] Assumed cable penetrators halved in costs due to improved design and integration with wet-mate connectors
[4] 1000m per downfeeder (2 off), 650m between machines (8 off), 1500 between rows (1 off)
[5] 1 static and 1 dynamic per downfeeder (2 off) & 2 of each per machine or row interconnection (2 off)
[6] 15 buoyancy units per downfeeder (2 off) & 30 buoyancy units per machine or row interconnection (2 off)

Table 27: Indicative mooring infrastructure costs based on proposed 10 machine array (nominally for P3 machine)

8.6 GRAPHICAL REPRESENTATIONS OF MOORING INFRASTRUCTURE COSTS

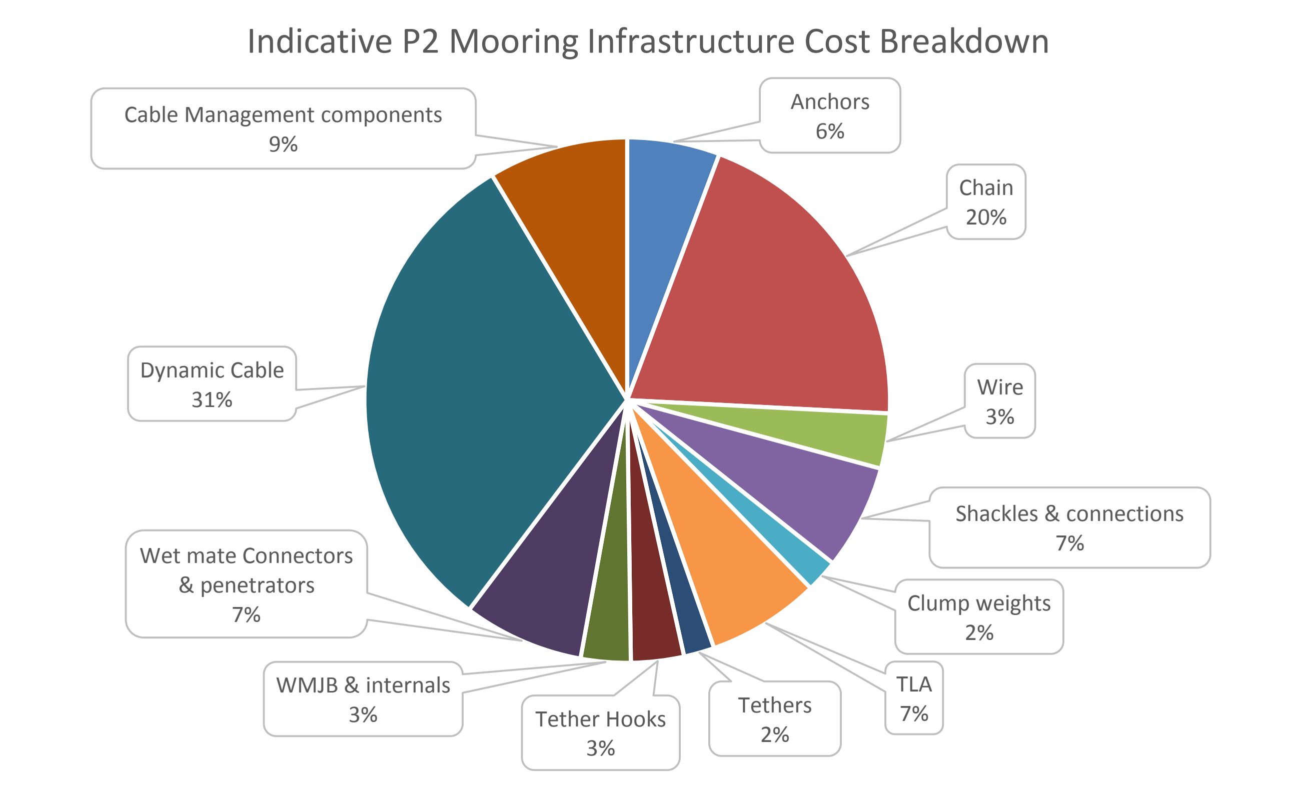


Figure 23: Indicative P2 Mooring Infrastructure Cost Breakdown

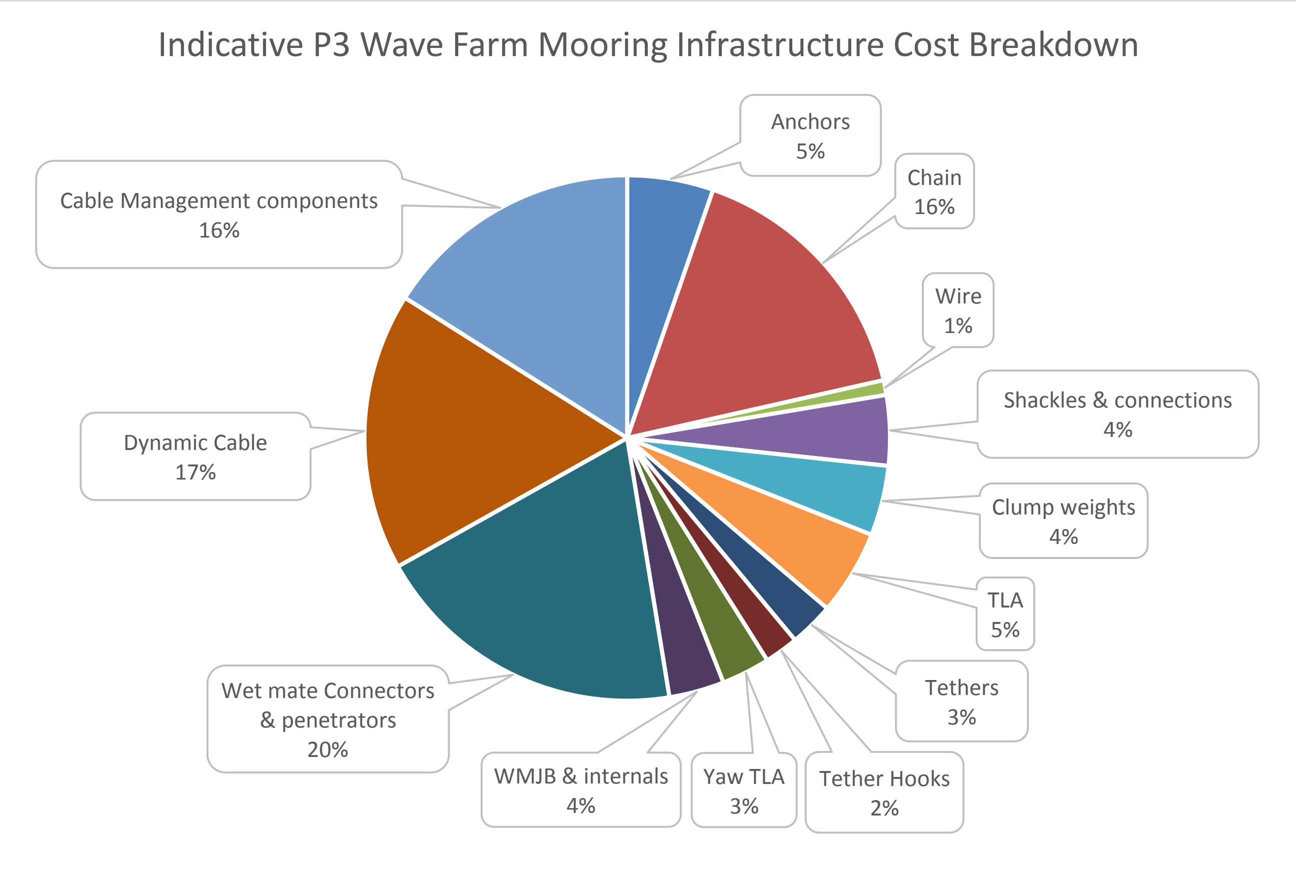


Figure 24: Indicative P3 Wave Farm Mooring Infrastructure Cost Breakdown