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HIGH LEVEL COST METRICS FOR WEC MACHINE ELEMENTS

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B1	22/07/2015	First Consolodated draft	BD	CT	
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Cost Metrics Spreadsheet Introduction

The purpose of this spreadsheet is to provide a concise 'ready reckoner' reference source for key components of the Pelamis system, to provide WES and partners with an easy sense checking reference for costings across programme areas and projects. The spreadsheet provides cost metrics for the main components of the Pelamis device and its associated moorings and connections systems, it is not a full and exhaustive list of every component rather a compendium of key costs and cost metrics from all of the main elements and systems. Summary pie charts illustrate the costs breakdowns for different systems and components types within the machine and the moorings.

Supplier names have been redacted.

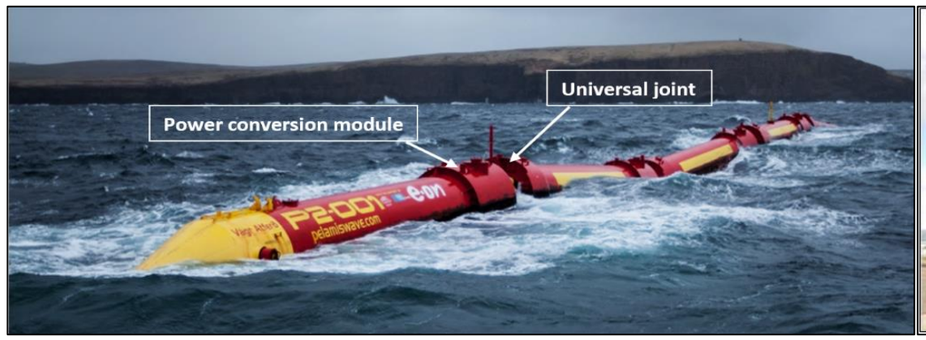
Separate worksheets then detail cost metrics and costs in their most practical form for individual components, systems, assemblies, or component types within the following sub-systems:

- Pelamis Main Structureal Components
- PTO Primary Transmission Components
- PTO Energy Storage Components
- PTO Secondary Transmission Components
- Miscellaneous Additional Components
- Mechanical Mooring Components
- SubSea Electrical Infrastructure

The majority of the costs used for this analysis are the actual costs for P2-002 (SPR) machine, procured in 2010/2011. These 3rd generation Pelamis systems had already benefited from the lessons learned through operation earlier Pelamis devices. The costs are thus representative of systems proven in operations. Some costs associated with the earlier P2-001 machine have been used where required.

All of the costs included in this document are discussed in more detail in the relevant cost metrics reports already delivered as part of Project Secure. The "PTO Cost Metrics" document (SEC-D-006) covers PTO system costs as well as costs associated with the main structural elements. The "Mooring & Connection Systems Cost Metrics" report (SEC-D-012) provides further information on the basis of the moorings and electrical infrastructure costs. Please refer to these documents for more detail on the values presented. These documents also bring together the cost metrics calculated into a number of example PTO and moorings systems and provide indicative costs for these example systems.

Illustrations of the Pelamis machine, PTO and moorings systems are included below for reference.



Ref.	Line/Component
1	Pelamis WEC
2	Yoke
3	TLA & Buoyancy
4	Tether Lines
5	3" Rear Line
6	3" Front Line
7	5 3/8" Mid-sections
8	Front line 5 3/8" section
9	Front anchor forerunner
10	Front anchors
11	Rear anchor
12	Dynamic Cable
13	Yaw Line
14	Yaw Clump

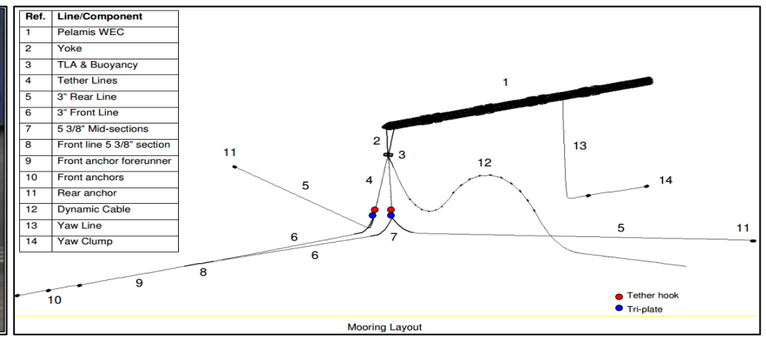


Figure 1: (left) P2 Pelamis machine in operation at EMEC, power conversion modules and universial joints identified. "Main tubes" separate the joints
(middle) Pelamis PTO system. Rams and their sealing elements are shown at the front of the main tube, the PTO secondary transmission is in the modules compartment and the accumulators and backup bottles are in the compartment behind that.
(right) Identification of P2 Main morring components

Main Assumptions

A number of assumptions have been made when calculating the cost metric values presented.

- All costs are based on one Pelamis machine's worth of components at the relevant quantities unless specifically stated. Where multiple items were purchased, purchase of one off items would incur additional cost per unit but, equally, economies of scale could be realised should quantities grow.
- Development and system assembly costs (e.g. labour, design effort, fabrication space) have not been included in this analysis. They are, however, commented on when they are known in the appropriate full cost metrics reports. Although these costs are not directly included in the metrics given, the impact of these on the overall cost of a PTO can be considerable.
- Similarly, delivery costs are not included in the analysis. Particularly for the moorings components, this cost can mean that the actual cost to the developer is significant higher that the part costs alone. However, given delivery costs are highly dependant on location and other commodity prices (e.g. fuel) they have been excluded here.
- Costs have not been adjusted to account for inflation or differences in commodity prices. The costs presented are predominently those incurred by PWP during build and manufacture of the P2-002 machines and are therfore mostly from 2010/2011. Where costs from differnt time periods have been used this is stated.
- Where accurate cost metrics can be defined they have been, although there is some element of estimation in some metrics or scaling factors defined. Any estimates made are based on sound engineering judgement and experience of how costs have varied over the history of the Pelamis development.

Additional Cost Drivers

The cost metrics presented throughout this document are derived or estimated from known P2 costs for components that were selected based on optimising the Levalised 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, doubling up on component to provide redundancy and fault tolerance may provide huge cost savings over the life of the project due to the fact the WEC may not need to be maintained as often and hence availability is increased. Similarly, overrating components such as filtration components to increase efficiency may pay dividends in terms of income over the project life. The additional drivers, as well as cost, that need to be considered when selecting components include:

- WEC availability
- PTO efficiency
- 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, selecting the most efficient system for the mean power output will not necessarily result in the highest power output over the project. The occurrence weighted efficiency, based on the time spent in different power regimes, need to be optimised to result in maximum efficiency gains.

Similarly, the reliability of minor, relatively cheap, components may have the most impact on machine availability. For example, analysis completed using PWP's O&M model (and discussed in SEC-D-004, the System Performance & Reliability Report) suggested that reliability of the ram pilot valves would have the biggest impact on machine availability and are a key component to focus on in this respect. However, this would not have been obvious without such detailed modelling of the overall system over the course of a project.

These drivers have not been dealt with thoroughly in this sheet. However, as the Pelamis P2 machines operated efficiently and effectively for extended periods we believe that the main components reported on here were of adequate design and construction to yield representative and reliable costs for components of this type in an early commercial machine.

P2 Pelamis Machine Captital Expenditure Cost Breakdown

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P2 Pelamis Structural Cost Metrics

Values extracted from "PTO Key cost metrics" report (SEC-D-006), section 6. Explanation & discussion on origin of values is available in this report.

P2 Main Structural Fabrications

Prices based on costs incurred by PWP during production of both P2 machines

Raw Material

Cost/tonne (steel raw material)	**£600**	Based on order of full quantity of various thickness & grades on a material take-off contract ('MTO')

Basic Fabrications

Large simple structures, e.g. cylinders and flat plates, with minimal deatials, connected pieces and alignment tolerances. A degree of automation already possible during production.

Typical cost/tonne (basic fabrications)	**£2,500**

Complex Fabrications

Large intricate strutures with many individual plate pieces, tight alignment tolerances and minimal possibililty of automation during production at this stage.

Typical cost/tonne (complex fabrications)	**£4,000**

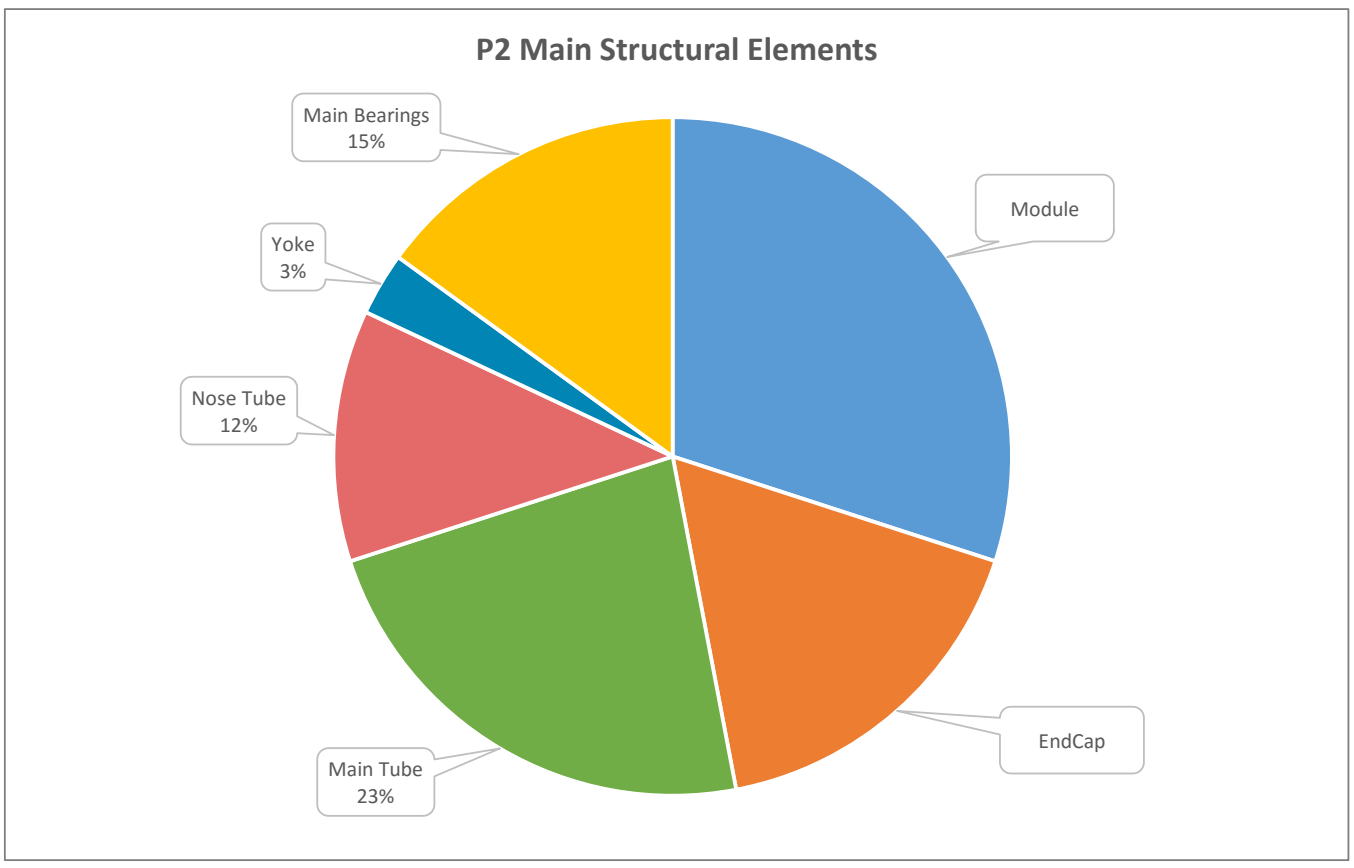
The metrics above are, in part, derived from the costs of the individiual main tube elements of the P2-002 Pelamis structure

Module Cost/Te	£4,100	(£184,500 each)
EndCap Cost/Te	£4,100	(£102,500 each)
Main Tube Cost/Te	£2,600	(£140,400 each)
Nose Tube Cost/Te	£3,350	* contains both complex and basic fabrications (£294,800 each)
Yoke Cost/Te	£4,100	(£65,600 each)
TOTAL COST FOR P2 MACHINE MAIN STRUCTURE	**£2,070,000**	

P2 Main Bearing Assembly

Based on P2 design & geometry (a large 2 degree of freedom universal joint allowing 30degrees of articulation). Costs associated with tooling are excluded. Costs do not include passive spring system and associated pneumatics.

P2 Main Bearing assembly (actual cost)	£90,400	
Cost/kg (radial bearings)	£40	
Cost/kg (axial bearings)	£31	
Cost/kg (full bearing assembly including main plate)	**£6**	* Main bearing assembly's mass = 15Te



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PTO Primary Transmission Cost Metrics

Values extracted from "PTO Key cost metrics"report (SEC-D-006), section 2. Explanation & discussion on origin of values is available in this report.

Hydraulic Cylinder Assembly

Based on costs for manufcature and assembly of P2-002 hydraulic cylinders (+/-30deg articulation range, 1.7MN push, 1MN pull, 210mm/200mm bore, 350bar working pressure, 1.8m strike, 5.5m total length)

Cost/kg (internal cylinder only)	£5.70
Cost/kg (fully assembled integrated cylinder inc. manifolds and trunnion bearings)	**£13.70**
Cost/kg (as above + REB assembly)	£12.60

The above metrics are based on the individual component costs for items in the cylinder assembly below:

Hydraulic cylinder	£12,500	*estimated split between cylinder and external parts & assembly
External Parts & assembly	£15,800	
Trunnion Bearing Elements	£4,700	
Flexible sealing Elements	£1,300	
Mounting Components	£1,200	
Manifolds & piping	£7,800	
Control & Instrumentation	£2,000	
TOTAL P2 CYLINDER COST (per cylinder)	**£45,300**	

Rod End Bearing Assembly (rolling)

Based on costs for manufacture and assembly of P2-001 rod-end bearings with roller elements (+/-30deg articulation range, 1.8MN, mass 2220kg)

P2 cost per bearing (bearing, seals, mounts & housing)	£23,800
Cost/kg (bearing only)	£10.80
Cost/kg (full assembly)	**£41.70**

Rod End Bearing Assembly (plain)

Based on costs for manufcature and assembly of P2-002 rod-end bearings with plain bearing elements (+/-30deg articulation range, 1.8MN, mass 1200kg)

P2 cost per bearing (bearing, seals, mounts & housing)	£16,400
Cost/kg (bearing only)	£13.70
Cost/kg (full assembly)	**£23.90**

Manifolds

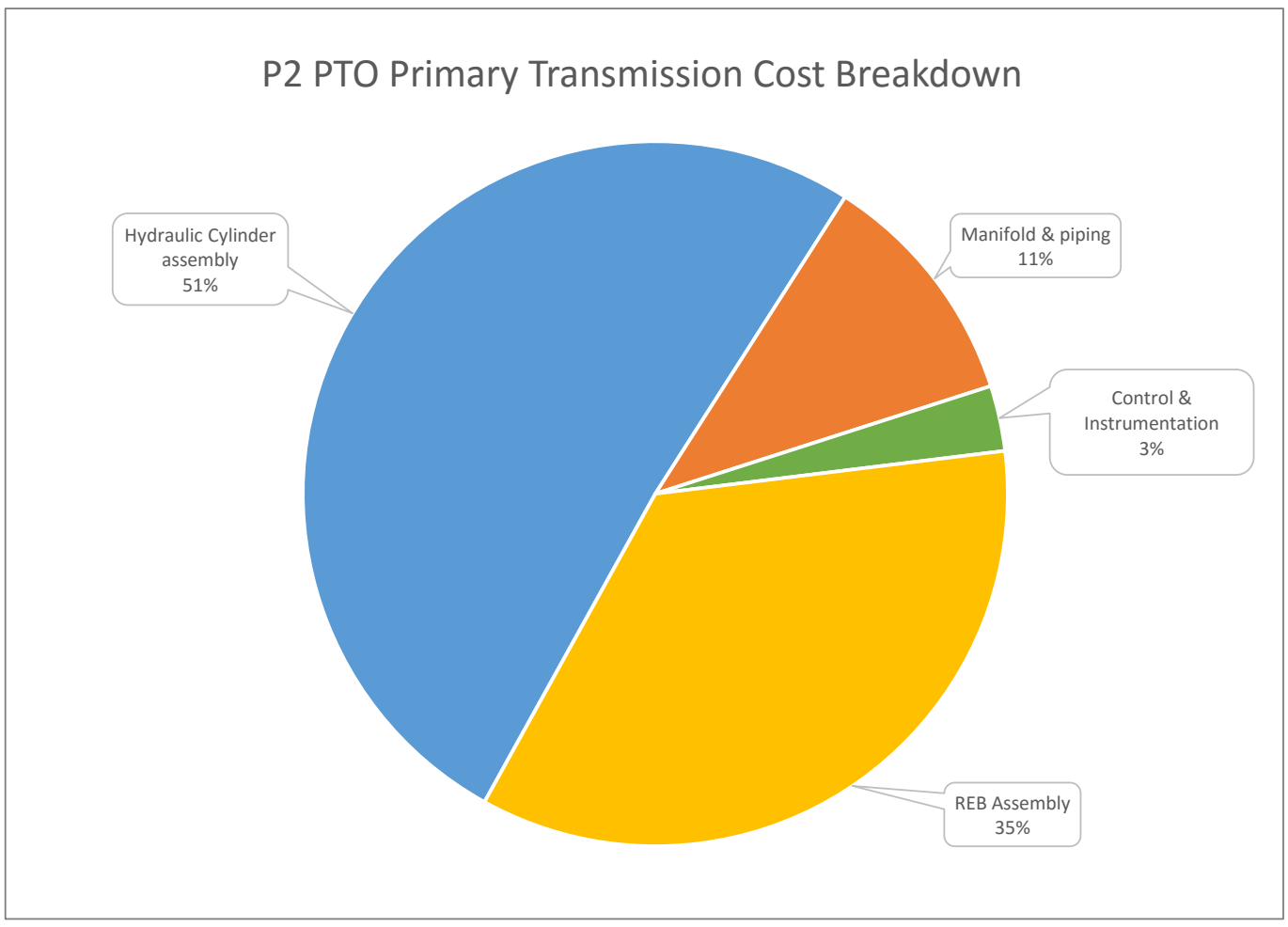
Based on historical mainfold prices (populated with all required valves) adjusted to 2010 levels

Cost / hydraulic cylinder	£5,700	
Cost/cubic metre	£180,000	
Cost/tonne	**£26,500**	* Volume quotes obtained indicate saving of approximately 40-50% are possible on large orders

Control & Instrumentation

Based P2 control system and including sensors, control cards, enclosures, and wiring

Total cost per hydraulic cylinder	**£2,000**



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Energy Storage Cost Metrics

Values extracted from "PTO Key cost metrics"report (SEC-D-006), section 3. Explanation & discussion on origin of values is available in this report.

Accumulators

Based on P2 accumulator design manufactured from standard mill lengths of tube for optimal value

P2 cost per accumulator (160L, 350bar w.p.)	£2,900	
Cost/kg (accumulators only)	£5	
Cost/L (accumulators only)	£18	
Cost/L (including gas connections, structure & pipework)	**£26**	* Gas connection and support structure cost ~£8000 per PTO

Accumulator Back-Up Bottles

Based on standard forged, mass produced, 350bar working pressure gas cylinders used in P2 machine (75L, 150L and 300L bottles available @ similar costs)

Cost/bottle (150L, 350bar w.p.)	£490	
Cost/kg	£3.60	
Cost/L	**£6.50**	

Reservoirs

Based on P2 reservoir design manufactured from rolled plate (up to 1800L vessels possible) with back-up bottle volume at 1.25 x reservoir volume

Cost per reservoir (1200L)	£7,825	
Cost/kg (reservoirs only)	£9.80	
Cost/L (reservoirs only)	£6.50	
Cost/L (Back-up bottle only)	£1.60	* L value based on Back-up Bottle capacity alone
Cost/L (including back-up bottles)	£8.50	* L value based on reservoir volume with BUB capacity @ 1.25x reservoir volume
Cost/L (inc. BUBs & support frames & connections)	**£11.90**	

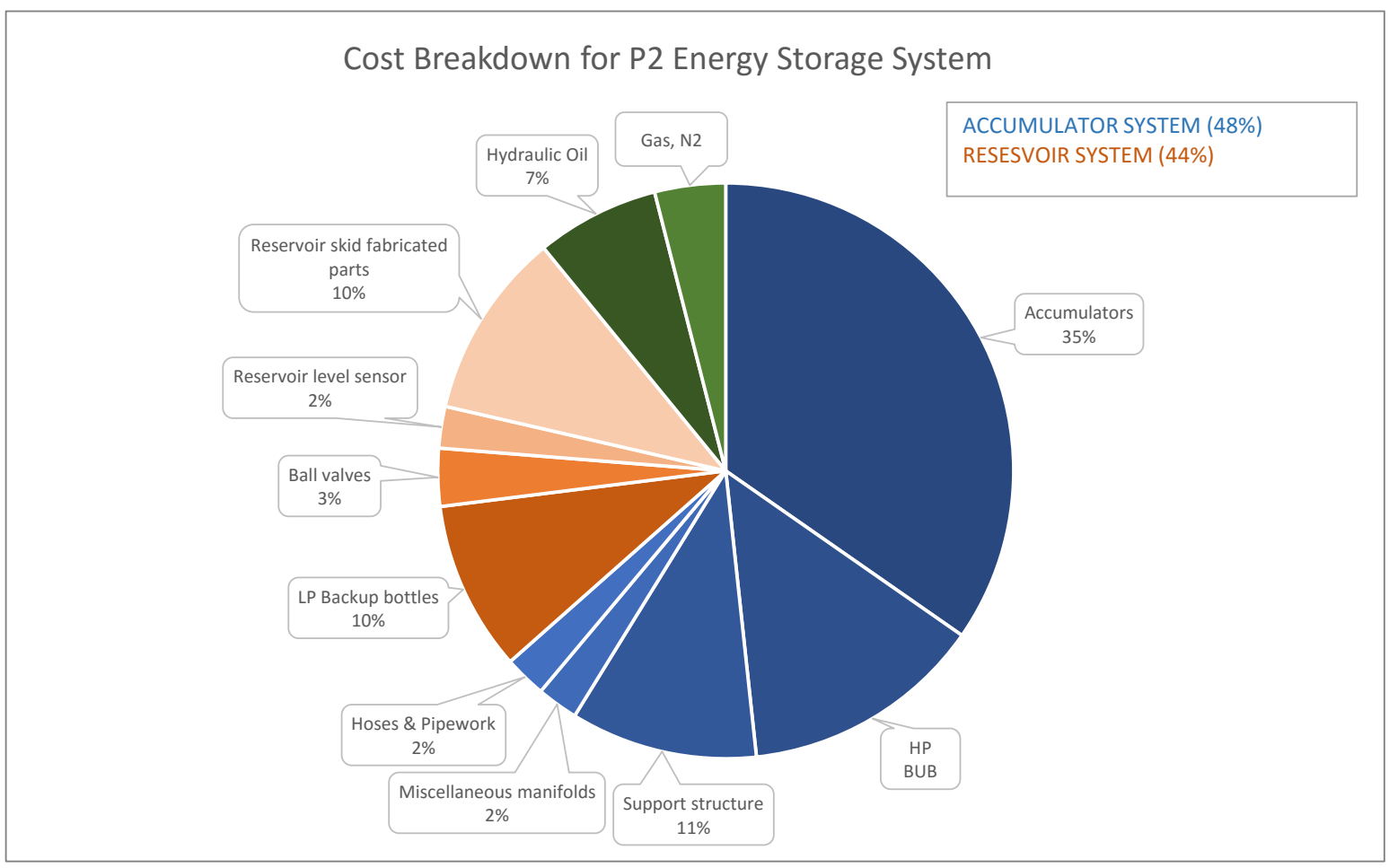
Hydraulic Oil & Nitrogen Gas

Premium grade hydraulic oil

Cost/L	**£1.75**	

Nitrogen Gas

Cost/PTO	**£2,000**	* includes hire of manifold cylinder pallets during assembly & commissioning



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PTO Secondary Transmission Cost Metrics

Values extracted from "PTO Key cost metrics" report (SEC-D-006), section 4. Explanation & discussion on origin of values is available in this report

Hydraulic Motors

Derived cost metric based on PWP purchased 350bar motors between 110cc/rev and 250cc/rev

Motor cost (60cc/rev)	£2,850
Motor cost (160cc/rev)	£4,270
Cost/cc displacement	**£30**

Manifolds

Based on historical mainfold prices adjusted to 2010 levels

Cost/cubic metre	£180,000	
Cost/tonne	**£26,500**	* Volume quotes obtained indicate savings of ~40-50% are possible on this on large orders

Filtration Systems

Based on PWP P2 PTO filtration systems. This included three independent filtration systems (primary filtration, offline filtration pilot filtration) and an optional fourth 'kidney loop' filtration system.

Cost/MG circuit (not including contamination sensor)	**£650**
Contamination sensor (each)	£900

Heat Management & Anti-Fouling

Based on "box coolers" as used in ship cooling systems and including temperature regulation & leak protection valves (heat rejection capability calculated assuming minimum water flow, maximum oil temperature of 60degrees and sea water temperature of 10degrees.

Cost/kW of heat dissipation (heat exchanger only)	£20
Cost/kW of heat dissipation (anti fouling only)	£4
Total Cost/kW (heat exchanger + anti fouling)	**£24**

Secondary PTO Ancilliary Hydraulic Equipment

Includes connecting pipework, hoses, clamps, ball valves, auxilliary pump/charger, pressure regulation and safety systems

Fixed Costs/PTO	**£6,000**	* these costs remain fixed regardless of PTO output
Variable costs for P2 system	**£10,000**	* these costs would increase with increased PTO output, Quoceant assumed these costs scaled roughly linearly with PTO rated electrical output.

MG Set Structure

Based on P2 MG support structure. Costs would scale with number and size of generators. Alternative metric for structural fabrications based on mass could aslo be used (see "basic structure" costs on structures page).

Cost for P2 MG support structure	**£5,500**

Generators

Based on cost metrics received from ABB during P3 design process for a range of generators from 100kW to 1MW.

Typical Cost/kW	**£60**

Low Voltage Switchgear

Based on P2 system (generators less than 150kW rating). Estimate given for larger generators.

Cost/generator (<150kW rating)	**£4,500**
Cost/generator (>150kW rating)	£5,000

Instrumentation

Based on P2 system including pressure sensors, temperature sensors etc. Quoceant believe similar costs would be incurred in any similar secondary transmission system.

Cost/generator	**£600**

Control System

Based on proposed P3 control system (predominently off-the shelf rather than bespoke components). Costs not affect by generator rating.

Cost/generator	**£2,500**

Wiring

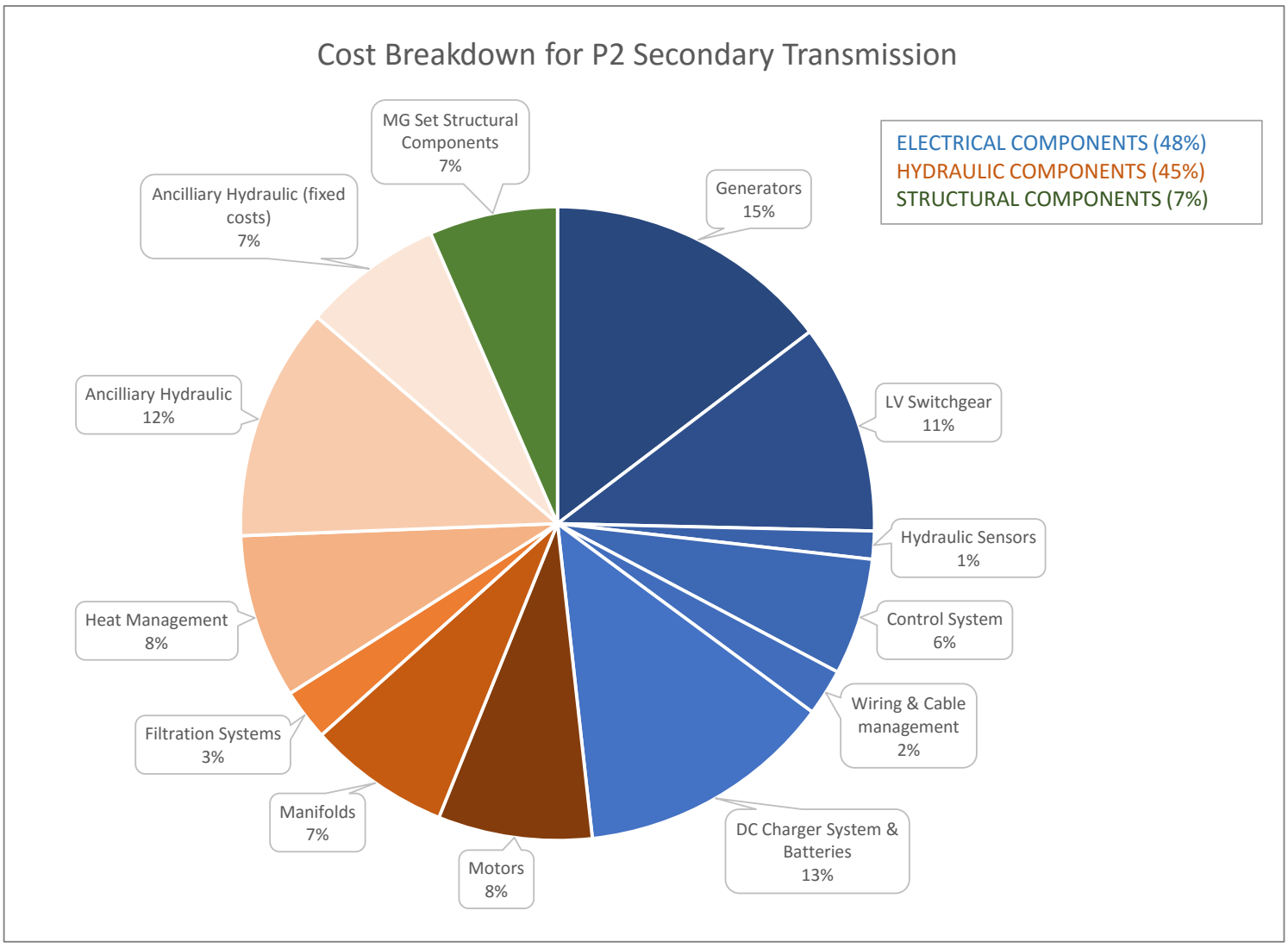
Based on P2 PTO. Costs not significantly affected by PTO rating.

Cost/generator **£1,000**

DC Supply & Battery Back-up

Based on P2 system and includes bateries, chargers, DC controls & ancilliary components. Costs are fixed regardless of number of generators or their rating.

Cost/PTO **£10,000**



Additional Electrical Systems Costs

Values extracted from "PTO Key cost metrics" report (SEC-D-006), section 5. Explanation & discussion on origin of values is available in this report. Costs provided based on P2 Pelamis system and/or quotes obtained for P3 wave farm. Quoceant cannot say how these costs might change for differently rated wave energy converters or systems.

P2 Transformer	£25,000	
STATCOM system (for grid code compliance)	£750,000	* Not required for P2 connection at EMEC but may be required for grid complience elsewhere
Composite flexible cable bundles (e.g. for cable transits) - Cost/m (MOQ 100m)		
Cable (a) - 3 off - 185mm², 1 off - 95mm², 10 off - 6mm²	£230	
Cable (b) - 6 off - 95mm², 1 off - 70mm², 6 off - 10mm²	£230	
Cable transit brackets and support systems (per transit)	£1,000	

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P2 Mechanical Mooring & Connection Components Cost Metrics

Values extracted from "Moorings & Connection Systems Cost Metrics" report (SEC-D-012). Explanation & discussion on origin of values is available in this report.

Tether Latch Assembly ('TLA') Body (mooring connection turret)

Based on fabrication costs for P2-002 TLA body

Total fabrication cost	£15,100
Cost/kg	**£11.20**

Tether Hooks

Based on fabrication costs for P2 moorings tether hooks

Total fabrication cost	£5,500
Cost/kg (profiling of main hook component)	£3.10
Cost/kg (main hook profiling & machining)	£7.80
Cost/kg (hook mechanism machined components)	£17.00
Cost/kg (full hook assembly)	**£10.60**

Wet Mate Junction Box

Based on fabrication costs for P2-002 WMJB. Fabrication cost included pressure testing and leak testing of sealed volume.

Total fabrication cost	£11,700
Cost/kg	**£25**

TLA Buoyancy Modules (depth rated to >100m but P2 operational depth c.25m)

Based on assembly & production costs of P2-002 TLA buoyancy unit (divinycell H100 closed cell foam, water-jet cut and assembled to correct shape then coated with fibreglass)

Cost/kg (Divinycell H100 buoyancy foam)	£16
Cost/kg (fully assembly buoyancy modules)	£37
Cost/Cubic metre buoyancy (fully assembly modules)	**£4,000**

Additional TLA Components

Based on assembly & production costs of P2-002 TLA

Fiberglass bullnose (excluding steelwork)	£1,500
Bullnose attachment, structure & ROV masterlink	£1,500
Miscellaneous fasteners, ratchet straps etc.	£1,500
Total Additional TLA Item Cost	**£4,500**

Synthetic Tethers

Based on P2 tether costs (ø125mm Gama98 rope, MBL 450Te, with filter elements between jacket and sub-rope core. Manufactured into 18m long tethers with modified K3-B thimbles each end overmoulded with PU)

Cost per tether	£5,390	
Approx. fixed costs per tether	**£4,000**	* fixed costs included splicing operation, thimble costs, PU overmoulding etc.
Base rope cost/m	**£80**	

Mooring Chain

Based on all stud link mooring chain purchased be PWP from 2009-2012

Cost/kg	**£0.95**

Wire Rope

Based on ø70m high strength, low rotation wire rope for P2 front anchor forerunners

Cost/kg (high strength, low rotation with rope)	**£4.80**

Based on all IWRC wire rope purchased between 2009 and 2012

Cost/kg (IWRC wire rope with spelter sockets each end)	**£2.80**

Connection Plates (Triplates)

Based on 150Te SWL triplates purchased for P2-002 mooring spread

Cost each	£1,300
Cost/kg	**£5**

Connection Plates (Triplates)

Based on all mooring shcakles purchased between 2009 and 2013

Cost/kg	**£5.40**

Anchors (Drag Embedment)

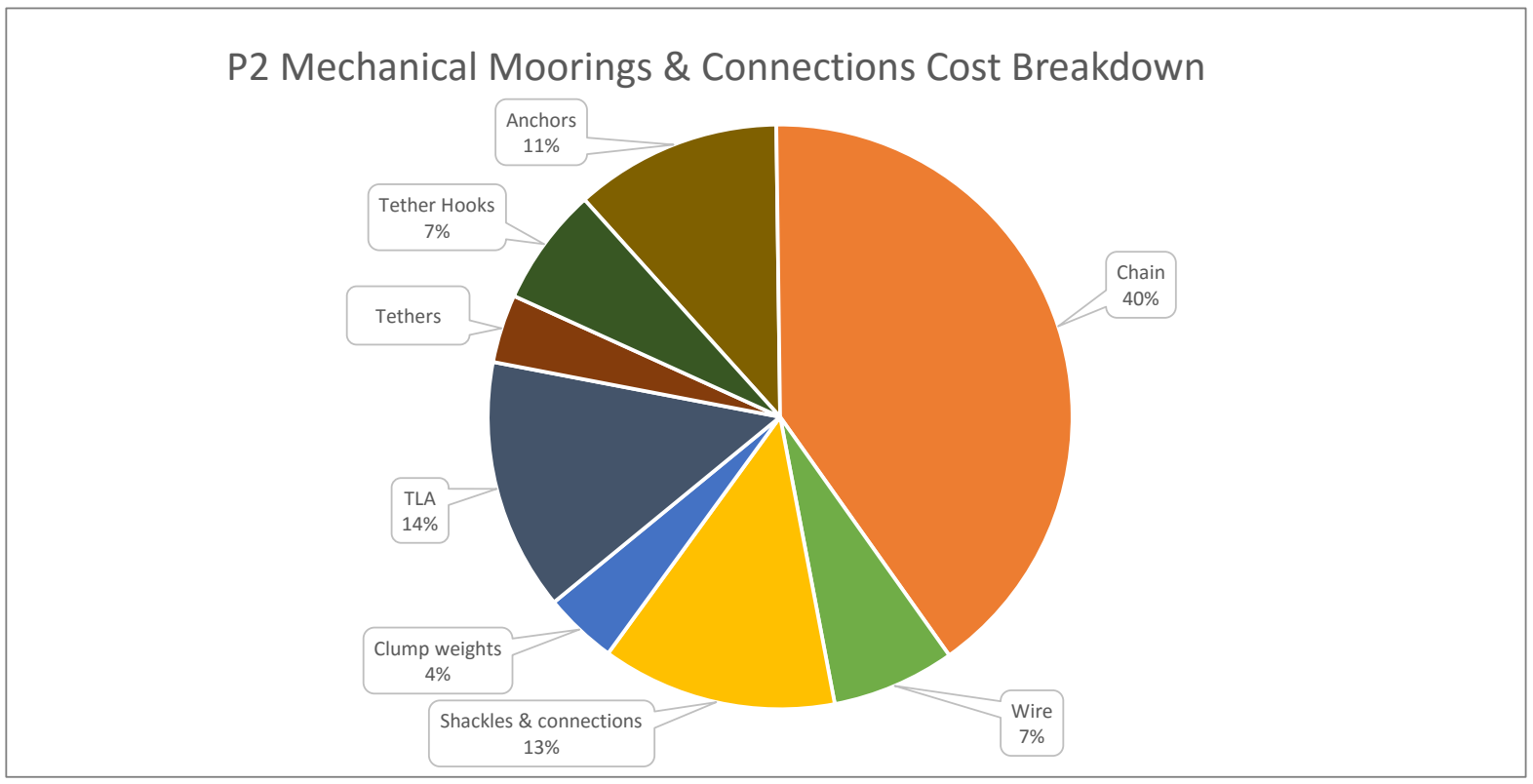
Based on non-OEM anchors purchased for both P2 mooring systems (OEM costs approximately double).

Cost each (3Te anchor)	£7,000
Cost each (5Te anchor)	£17,000
Typical Cost/kg	**£3**

Clump Weights

Based on clump weights purchased for both P2 mooring systems, (chain used was secondhand)

Cost each (36Te clump)	£9,500
Cost each (6Te Chain clump)	£2,250
Cost/Te (block clump weights)	**£270**
Cost/Te (chain clump weights)	**£330**



P2 SubSea Electrical Mooring & Connection Components Cost Metrics

Values extracted from "Moorings & Connection Systems Cost Metrics" report (SEC-D-012). Explanation & discussion on origin of values is available in this report.

Power Wet-Mate Connectors

No single metric derived due to different connector specifications - information obtained by PWP provided below. In PWP's experience, dry-mate connectors are not available at a signifcantly reduced cost therefore, regardless of application, wet-mate connectors were the connectors of choice for P3 infrastructure due to increased felxibility of connection.

Manufacturer	Rated Voltage	Rated Current	# of pins	Max. cycles before maintenance	Cable Cross Sectional Area	Test voltage	Approx. cost per mating pair	Information source
Company A	11kV	250A	3	>100	Not specified	Not specified	£140k	E-mail & datasheet, 2014
Company B	6.6kV	100A	4	>100	>95mm2	15kV	£20k	Quote & datasheet, 2012
Company C - type 1	11kV	250A	3	Not specified	70mm2	43.2kV	£30k	Quote & datasheet, 2013
Company C - type 2	11kV	400A	3	Not specified	-	-	£50k	Quote & datasheet, 2013
Company D	8.7kV	220A	3	100	35mm2	20kV	£70k	E-mail & datasheet, 2010
Company E	8kV	220A	3	100	No details	No details	Not quoted	Website
Company F	7.2-33kV	500A	3	No details	No details	No details	unknown	website, 2014
Company G	11kV	400A	3	No details	No details	32kA	~£220k	E-mail & datasheet, 2012

Indicative volume discounts were discussed with one manufacturer. Indicative discounts:

Quantity Ordered	Discount
1off	0%
10off	33%
100off	50%

Communications Wet-Mate Connectors (Copper Ethernet)

Price based on P2 costs for copper pin Ethernet wet mate connector

Cost per pair **£11,000**

Communications Wet-Mate Connectors (Fibre Optic)

Price based on e-mail quote for suitable fibre optic wet-mate communications connector

Cost per pair (1 off) **£23,000**

Cost per pair (35 off) £12,000

Dynamic Cable

Dynamic cable costs vary widely and are suseptible to changes in the price of the raw material (copper). Cost is greater than for static cable due to need for cable to dynamic load specification and need to be completely torsionally balanced. Prices shown below are based on quotes received by PWP during 2013.

Manufacturer	11kV, 500mm² Static Cable (QTY - 1500m), £/m	11kV, 120mm² Dynamic Cable (QTY-3000m), £/m	Project Management Cost (£) - inc. dynamic analysis
Company A	£268	£210	£973,000
Company B	N/A	£147	£50,000
Company C	£416	£188	£366,000

Cable Buoynacy & Ballast Modules

Price based on P2 costs for cable management systems

Cable Management Costs	Cost each
Cable buoyancy (100kg)	£600
Cable ballast (40kg)	£300

Cable Touchdown Clump Weight & Rigging

Price based on P2 costs for cable management systems

Cost per clump & rigging **£8,000**

Dynamic Bend Stiffeners

Price based on P2 costs for cable management systems

Cost per unit **£12,000** * estimated costs for similar bend stiffener for static application = £10,000