Quoceant Ltd

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PTO SYSTEM COST METRICS

PROJECT SECURE – DELIVERABLE 2-4

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ABBREVIATIONS

PTO	Power take-off
WEC	Wave Energy Convertor
DOF	Degree of freedom
MIMO	Multi Input, Multi Output
DNV	Det Norske Veritas
STATCOM	Static synchronous compensator used for power conditioning
LV	Phase-to-phase voltage between 100 V and 1,000 V
MV	Phase-to-phase voltage between 1,000 V and 35 kV
COTS	Commercial Off The Shelf
HP	High Pressure
LP	Low Pressure
PWP	Pelamis Wave Power
MOQ	Minimum Order Quantity
O&M	Operations and Maintenance
LCoE	Levelized Cost of Energy
SG Iron	Spheroidal Graphite cast iron
REB	Rod End Bearing
BUB	Back up bottle

EXECUTIVE SUMMARY

Consistent with previous reports, the P2 PTO system has been divided into Primary and Secondary stages and the Energy Storage system. For each stage, a breakdown of the key components is detailed and cost metrics are provided in the most practical format in each case. The majority of the costs used for this analysis are the actual costs for P2-002 machine, procured in 2010. These 3rd generation PTO systems had already benefited from the lessons learned through operation earlier Pelamis devices and are representative of a proven PTO system. Some costs associated with the earlier P2-001 machine have been used where required. From the analysis completed the following key points should be highlighted.

- The cost of the system is obviously dominated by the cost of the larger components, however, the cost of integrating the key components into a functional power take-off system should not be underestimated. Based on the metrics derived this 'integration cost' can be as high as 2 times the cost of the major components, e.g. the accumulators and reservoirs each only contribute 55% of the overall cost of using reservoirs in the system. This additional cost covers the back-up bottles and ancillary components such as mounting brackets, fittings, hoses and tooling.
- It is important to understand that the lowest cost option 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. The cost metrics presented throughout this document are derived or estimated from known P2 costs for components that were selected based on optimising the LCoE for the Pelamis as a whole.
- Looking at the overall PTO system costs and how they can be attributed by system, for the Pelamis P2 WEC, the Primary transmission system is the dominant cost, accounting for 65% of the total PTO cost. The energy storage system accounts for 15% and the secondary transmission system, the most readily transferrable technology with PWP's PTO design, is only 20% of the total PTO cost.
- In terms of cost increases with scale, as WEC ratings increase significantly, the cost of Primary transmission will increase more rapidly than the cost of Secondary transmission and energy storage.

The cost metrics derived throughout the document are based on the following assumptions:

- All costs based on one Pelamis machine's worth of components at the relevant quantities. 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. 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.
- 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 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.

Appropriate cost metrics have been derived for each of the major components and their associated parts and are presented throughout the document. For the primary PTO components, cost per unit weight or volume is likely the most relevant metric for each of the different types of technology described. For the secondary PTO system, the cost per kW of electrical rated power is provided where possible or additional metrics such as cost per generator have been defined. In each section the scalability of the particular system in question has been discussed. Due to the modular nature of the energy storage and secondary systems, they lend themselves

very well to scaling up. The use of additional energy storage vessels increases fault tolerance and has assembly benefits. The ability to choose differently rated motor/generator units in the secondary transmission also enables good part-load efficiency to be achieved in addition to the fault tolerance and assembly benefits.

Broadly speaking, the energy storage system and Secondary transmission contribute similar proportions of the cost to the overall PTO costs. Their contributions have been shown to remain roughly consistent for the P2 (as built) design and the P3 (well evolved design) machine that was planned. The most dominant costs in the energy storage system, as expected, are the vessels themselves. In the Secondary transmission, the motors, generators, manifolds and switchgear alone account for roughly half the overall system cost.

At the end of the document the cost metrics are brought together to give example costs for secondary PTO systems (including energy storage) of different electrical ratings ranging from 205kW (the P2 module electrical rating) to 1MW. These estimates are based on the PTO system demonstrated in the P2 machines. Work completed prior to PWP administration on costing the larger next generation P3 machine has been included or referenced where possible. From these differing sets of figures costs for larger secondary PTO systems have been estimated.

We have specifically avoided trying to estimate costs for the primary PTO components for differently scaled PTOs. Implementation of the Primary PTO stage is very device specific and therefore the subject of large uncertainty. Furthermore, significant design and analysis work would be required to provide meaningful estimates for an up-scaled P2 system hence, for the Primary PTO system, cost estimates for the up-scaled systems have not been provided.

The summary figures for the different PTO ratings are shown below. Significant cost savings can be achieved by moving to a 435kW electrically rated system but at higher outputs the savings are less significant. Some design optimisation has been included in the 435kW system based on P2 experience but much of the cost savings are attributable to the fixed costs not scaling with power output. The increased costs to account for the larger flows in the higher rated systems reduce the cost savings possible.

	Secondary PTO System & Energy Storage			
PTO Sustained Output Rating in peak cond's (Max electrical rating)	**140kW** (205kW)	**300kW** (435kW)	**450kW** (685kW)	**670kW** (1MW)
Cost estimate	*£150,000*	£237,000	£360,000	£501,000
£/kW (sustained output power)	£1,098	£817	£788	£752
£/kW (max electrical rating)	£732	£545	£526	£501

Defining the power rating of a PTO system is difficult. The maximum electrical rating is the easiest to define but, variations in absorbed power can vary +/-50% about the sustained output level in larger seas. The maximum sustained output power is thus only a proportion of the electrical rating and has been defined in this document as the electrical rating divided by 1.5. This enables the system to deal with the power fluctuations and cost metrics according to both ratings are given.

Whilst out with the defined scope of the report, a section has been included to highlight the relationship of the WEC structure and joints system to the Primary PTO stage. A WEC's cost will be dominated by the cost of the large structural elements required to absorb power. When the costs of the Primary and Secondary PTO systems are compared to those of the structure and mechanical systems required to provide the prime mover, the scale of the difference in costs makes it clear that primary PTO components should be selected to optimise the costs of the main structure. As such, more expensive primary PTO components may be required but the overall cost of the WEC may be reduced.

1. INTRODUCTION

The Pelamis PTO can be split into three main parts: Primary transmission, Secondary transmission, and the Energy storage that lies between them.

The primary Transmission is the WEC device specific part of the system that absorbs the power from the wave induced motions of the structure and passes it to the energy storage system. In the Pelamis system, this comprises hydraulic rams (or cylinders), the bearing and sealing systems that connect them to the structure, their control manifolds and valve gear, and the hoses and pipes needed to connect them to the rest of the PTO. The secondary transmission and the energy storage system are more generic and transferrable as they do not directly interact with the WEC structural response.

The secondary transmission comprises the motors and generators that convert the stored hydraulic pressure into electricity, the electrical panels to control them, plus all the PTO functions not in the primary transmission, these include; pressure and temperature regulation, fluid filtration, and protection systems.

Energy storage comprises high-pressure gas accumulators, with back-up bottles, and their structural housings and fluid connections. The low pressure fluid reservoirs (statically boosted in the Pelamis system), are also included here for costing purposes as they are sized in direct proportion to the energy storage volume (when fluid is not in the accumulators it is in the reservoirs)

Taken across all aspects of the design, it is Quoceant's experience that, while some major principles can be understood to direct development strategy and project a scaling path for technology development, detailed design work is required at each stage even to provide estimates of costs of structures and primary load transmission elements. This makes it inappropriate to attempt to generalise cost metrics for the bearing systems and connection points of the primary transmission. However, it is possible to benchmark the as built P2 Pelamis system in all respects of its PTO system, and to provide the example of cost projection of a larger P3 machine that was under development. This issue is expanded on in section 5.

Useful metrics of power rating versus cost can be readily provided for major aspects of the PTO system and this work package is primarily focussed on these. However, this should be taken in the context of the wider impact of PTO systems on the cost of the WEC and other economic factors driven by the PTO systems such as reliability and controllability for increased absorption.

	Costs for 205kW P2 joint
Primary Transmission	£276,000 (65%)
Secondary Transmission	£84,000 (20%)
Energy Storage	£66,000 (15%)
Total	**£426,000**

Figure 1 Hydraulic PTO cost of P2 Pelamis

1.1 A NOTE ON RATING

The rating of a PTO system is a potentially confusing subject. The simplest way to define a PTO rating is based on the combined rating of the electrical generators. However, this rating is not achievable on a sustained basis due to fluctuation in resource and power absorption. A sensible alternative metric is the sustained average output in peak power conditions. This is the power level around which the instantaneous output varies as pressure fluctuates in the energy storage system between wave groups.

For the size of energy store selected for the P2 system, the power fluctuates around 50% around the average in peak conditions, but much less in smaller conditions. This means that the hydraulic motors need to be sized to deliver around 1.5 times the nominal rating when at peak pressure and displacement. This ratio could be smaller with a larger energy store, or the energy store could be smaller if greater power fluctuation were acceptable. However, the relative sizing represents what was understood to be a good compromise on all fronts.

Throughout the document, up until the section 7 that provides example PTO systems and their estimated costs, the total electrical rating has been used when defining metrics for ease of definition (adjusting the rating at each point would have been overly complicated). However, once the cumulative system costs are considered it is appropriate to state the cost/kW according for both rating definitions (where the electrical rated power is 1.5 times the sustained output power). Both have been included in the estimated system costs tables.

1.2 ADDITIONAL PTO DESIGN 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. 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.

2. PRIMARY TRANSMISSION

As previously discussed, the primary transmission for the Pelamis P2 consists of the following main components and systems:

- Hydraulic cylinder assembly.
    - Hydraulic cylinder/actuator
    - Trunnion (rear) bearing
    - Ram manifold, piping and connections
    - Ram control and instrumentation
- Rod end bearing (2 DOF, 30 degree of articulation)
    - Rolling element design
    - Maintenance free design

Cost metrics associated with the primary PTO elements are provided in this section such that they can used comparatively when reviewing other technologies. However, it is imperative to realise that these costs are provided out of context of the selection process and optimisation that lead to the component specifications. In most cases the technology selection and design were optimised, together with the structure and bearings systems, to create the lowest combined cost rather than the lowest individual part cost.

This is likely to be true of any primary PTO technology and hence it is not useful to provide £/kWh metrics for individual components. Instead, indicative values per tonne, MN or other relevant metric are provided along with commentary.

Table 1 details the summary costs and metrics for a combined P2 joint system.

	Quantity	Cost	Proportion	Total	£/ kw rated
Hydraulic cylinder assembly	4	£45,200	65%	£180,800	£880
Rod end bearings (P2-001)	4	£23,800	35%	£95,200	£460
				£275,800	**£1350**

Table 1: Primary power take off for P2 joint (205kW)

Note that in an alternative WEC platform, the primary transmission could comprise quite different operating principles and component types, and even for a similar WEC, alternative architectures could employ rotational actuators or different combinations of hydraulic cylinders.

Because there is such an important relationship between the primary transmission and the supporting structure, Section 6 in this report details the costs and some high level metrics associated with the Pelamis P2 structural and mechanical systems. Also discussed is the related issue of scaling of the primary transmission and hence the reasons we have not provided primary transmission costs for the example integrated PTO systems costed in section 7.

2.1 INTEGRATED HYDRAULIC CYLINDER ASSEMBLY

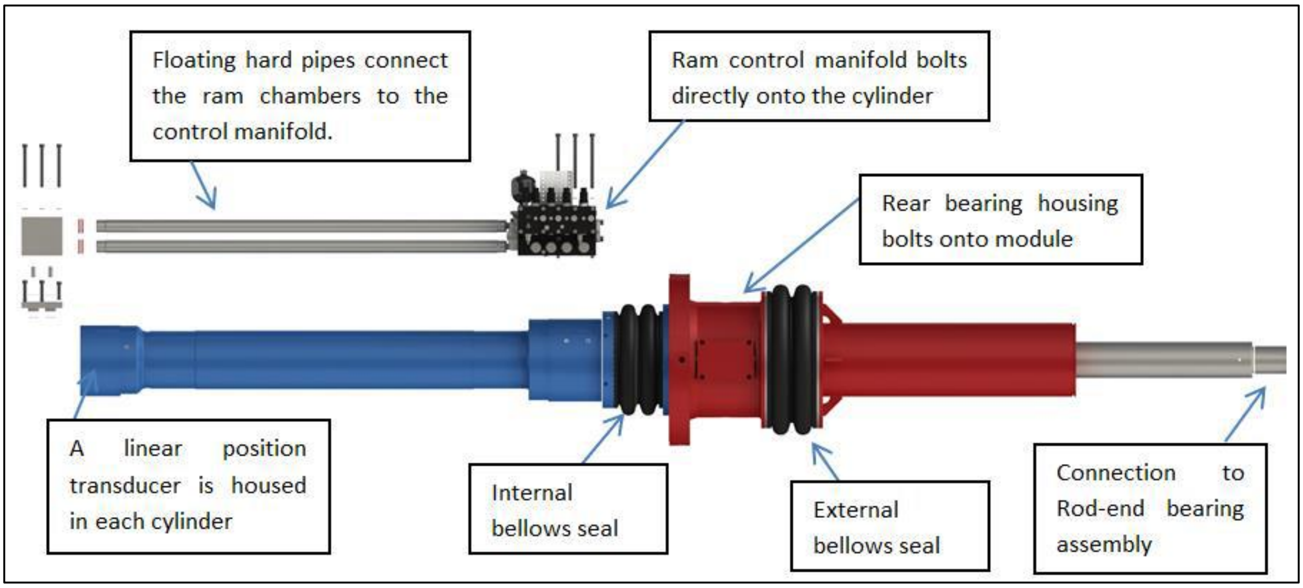

Figure 2 : Schematic of hydraulic cylinder assembly

The major element of the Primary transmission is the integrated cylinder. This product was developed and manufactured by a number of parties to meet the requirements of the Pelamis WEC. The engineering development, detailed design, and tooling costs incurred by Pelamis and the suppliers were kept separate and hence are not included in cost breakdowns. Other costs have been broken down in an attempt to provide useful insight into the relative costs of features that will be common to many other WECs. The table below and the pie chart overleaf details the main sub components and their relative contribution.

	Cost	%
Hydraulic cylinder *	£12,500	28%
External parts and assembly *	£15,800	35%
Trunnion bearing elements	£4,700	10%
Flexible sealing elements (bellows)	£1,300	3%
Mounting components	£1,200	3%
Manifold and piping	£7,800	17%
Control and Instrumentation	£2,000	4%
Total	**£45,200**	**100%**

Table 2 : Cylinder sub component costs

* Following a collaborative design programme between PWP and the supply chain, the cylinder was procured as a complete assembly where PWP free issued a number of components including the trunnion bearings and bellows seals. As such there is not an accurate split for the hydraulic cylinder separate to the external parts (assembly & test) but a well-informed estimate is provided.

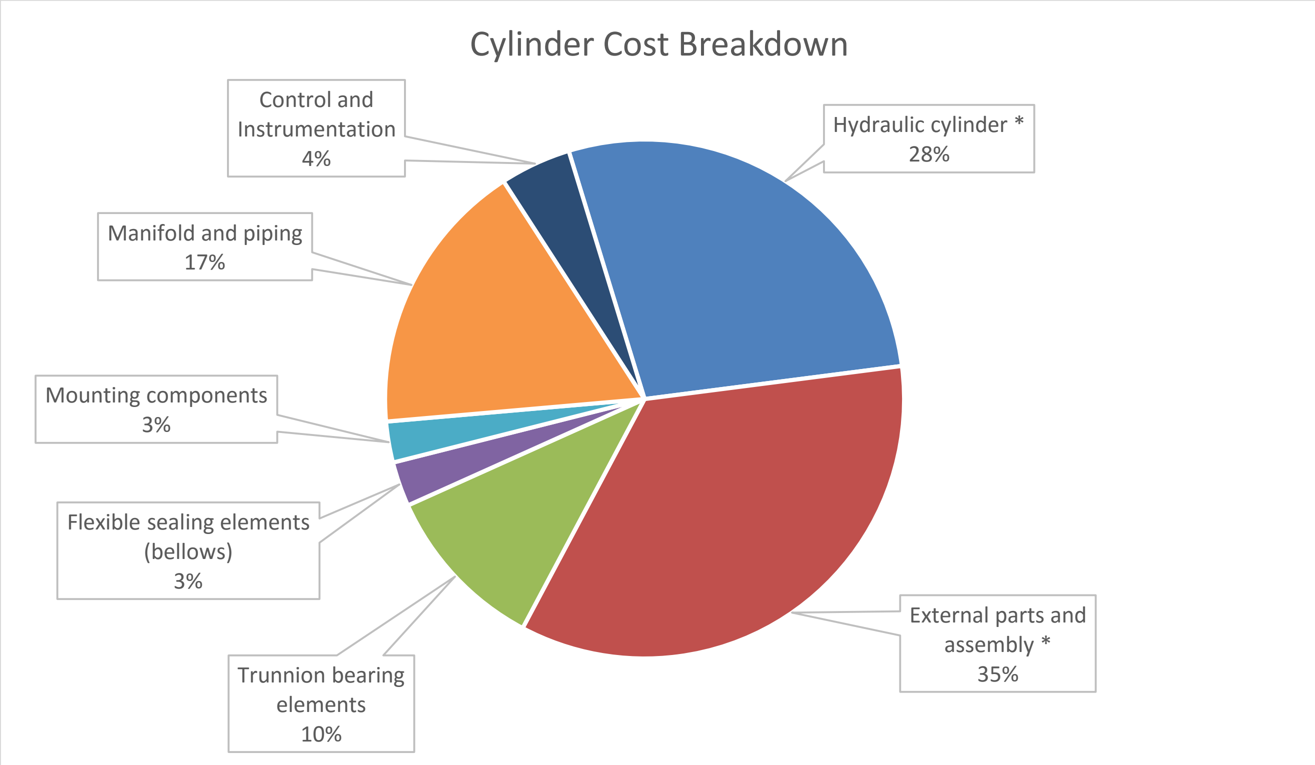

Figure 3 : Integrated hydraulic cylinder component cost distribution

Table 3 details some of the key cylinder specifications. This data can be used as a basis for other metrics or comparisons.

	Value	**Comment**
Cost each	£45,200	Includes internal position sensor
Articulation range	+/- ~5 degrees (rear)	Typical angles in service were less than +/-2 deg.
Static/dynamic load rating	~1.7MN push 1MN Pull	
Bore	210mm / 200mm	Front / Rear. Tandem design
Max WP	350bar	
Stroke	1.8m	
Overall length	5.5m	
Weight each	~3300kg (~2200kg)	Including manifold and piping (cylinder only)
Estimated life	~10years	Seal life uncertain due to unfamiliar operating regime. Hugely dependent on the oil cleanliness.

Table 3 : Key cylinder assembly specifications

	£/kg	**Comment**
Internal cylinder only	£5.70	Estimated, no bearings, housings or external seals
Cylinder assembly	£13.70	Integrated assembly Including manifolds and trunnion bearing
Assembly and bearings	£12.60	Full assembly including REB

Table 4 : Key metrics for the cylinder assembly

2.1.1 CYLINDER TRUNNION BEARING (REAR BEARING)

For reasons of joint geometry and environmental sealing the P2 cylinder utilised a spherical trunnion bearing mounted near the centre of the cylinder. The bearings were mounted in a tubular steel housing which was sealed to the cylinder by compliant bellows. This housing mounted directly to the module structure and provided the 2 degrees of freedom necessary. This bearing design allowed the cylinder and bearing to remain in a dry environment and provided convenient access to the ram control manifold from inside the module structure. A schematic is shown below.

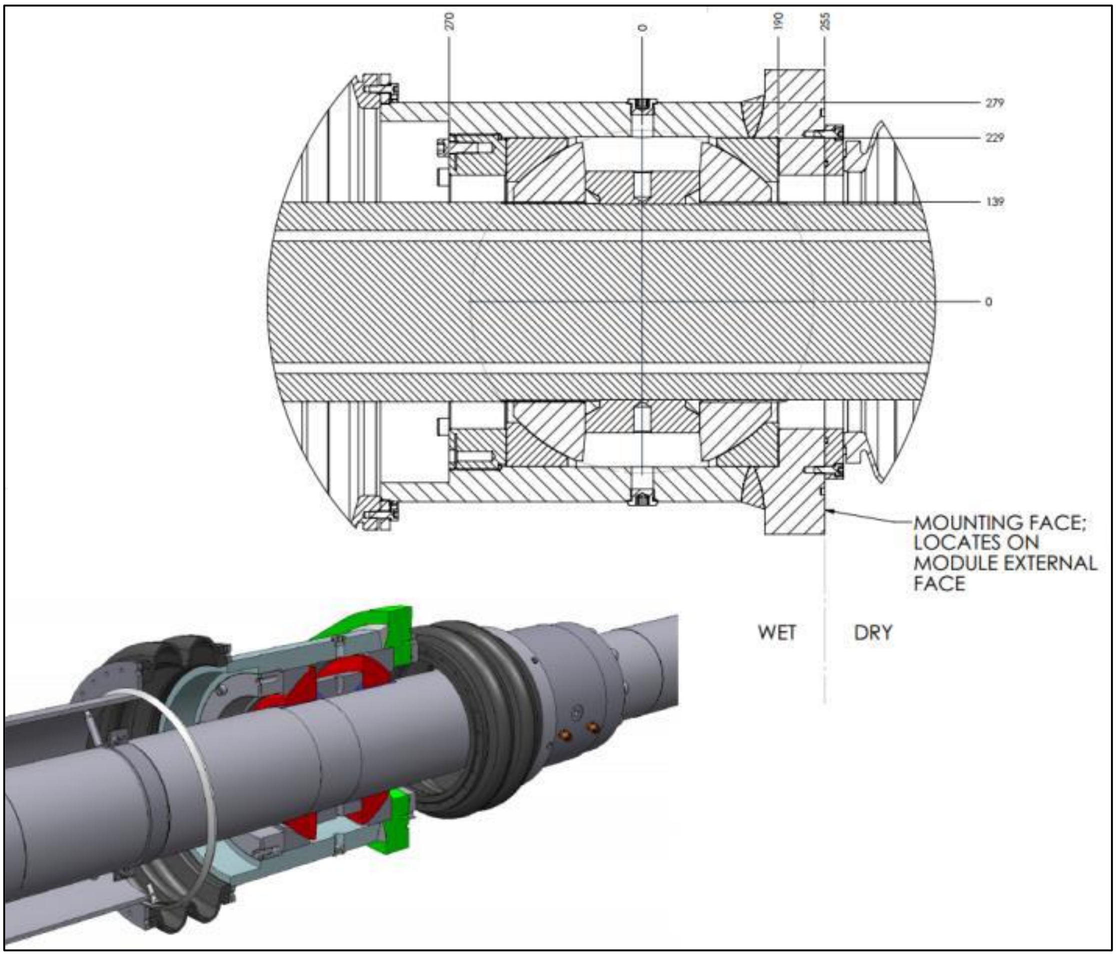

Figure 4 : Spherical trunnion (body) bearing, highlighted in red. Module interface is highlighted green.

The nature of the design meant that the load rating of the catalogue bearing was significantly greater than required however the predicted life meant replacement or refurbishment would be required.

	Value	Comment
Articulation range	+/- ~5 degrees (conical)	Typical angles in service < +/-2 degrees.
Static load rating	~28MN (2800 tonnes)	Significantly over rated for peak load
Dynamic load rating	~17MN (1700 tonnes)	Significantly over rated for peak load
Cost each	£2,350	Excluding housing/mounting
Weight each	84kg	Excluding housing/mounting
Calculated life	5-10years	Uncertainty due to unfamiliar operating regime.

Table 5 : Key trunnion bearing parameters

The only useful metrics for this bearing element is the cost per unit weight which was £28/kg based on the volumes used by PWP. However, this figure is sensitive to the volumes produced by the supplier. At the time, this size of bearing was quite popular and both larger and slightly smaller bearings were relatively more expensive.

An alternative cardan arrangement using four, lower cost, journal bearings is also possible but for the P2 implementation, this would have required a larger and significantly more expensive housing and environmental sealing arrangement. A single spherical eye type rear bearing would have been significantly lower in cost but would have resulted in a decreased the buckling capacity of the cylinder, reduced bearing life and increased the length (weight) of the module structure.

2.1.2 RAM MANIFOLD

Each of the main hydraulic rams has a manifold attached to it which controls its response to the wave induced loads and its energy absorption. The manifold is a core component of the primary PTO, its valve set and hydraulic circuit has been developed in conjunction with the valve and manifold manufacturer since the first full scale test rig in 2002 and all of the subsequent full scale Pelamis machines. As it is in the primary flow path between the ram, the accumulators and the generators, pressure drop through the valves and ports in the manifold directly impacts on the efficiency and economics of the machine. The main valves are oversized or in some cases doubled up in parallel to reduce the pressure drop, this increases the cost of the manifold but is justified by the increased yield of the machine. In addition to the main control valves, the manifold also includes failsafe circuitry and control valves which operate the ram if there is a higher level systems failure.

Based on historical large manifold prices (adjusted for inflation to 2010 levels) the cost of all of the similar, densely packed manifolds including valves, assembly, engraving and plating has remain remarkably consistent for all manifold purchased up to the P2-002 build. This analysis included all the PTO system manifolds from the ram manifolds, to distribution manifolds, the motor manifolds and main manifolds. The costs metric for a fully populated manifold are:

Metric	Cost
Cost / m^3	£180,000
Cost / tonne (SG Iron or Steel)	£26,500

Table 6: Key Cost metrics for fully populated manifold assemblies

The figure below is an extract from the spreadsheet used to calculate the above manifold metrics. It shows the ram manifold costs that were obtained during the quotation prior to the P2-002 build. Two of the manifold manufacturers were unwilling to quote for the small quantities required at the time but did provide quotes for the manifolds if they were produced for volume manufacture. It is apparent that large cost savings of near 50% would be realised once large volumes of manifolds are being manufactured.

Company	Year	Machine	Manifold description	Cost source	£	w	h	d	Volume m^3	£/m^3 (2010)	£/tonne (2010)
	2010		SPR ram main		£ 2,430	0.305	0.23	0.364	0.0255346		
A	2010	P2-002	FSV Cheek	Quote	£ 940	0.129	0.364	0.125	0.0058695	£ 120,864	
	2010		LP cheek		£ 760	0.076	0.364	0.1	0.0027664		
			Valve cost		£ 1,763	Cost including valves & assembly				**£ 172,452**	**£ 24,636.04**
	2010		SPR ram main		£ 765	0.305	0.23	0.364	0.0255346		
B *	2010	P2-002	FSV Cheek	Quote	£ 334	0.129	0.364	0.125	0.0058695	£ 40,603	
	2010		LP cheek		£ 289	0.076	0.364	0.1	0.0027664		
			Valve cost		£ 1,763	Cost including valves & assembly				£ 92,191	**£ 13,170.13**
	2010		SPR ram main		£ 2,435	0.305	0.23	0.364	0.0255346		
C	2010	P2-002	FSV Cheek	Quote	£ 947	0.129	0.364	0.125	0.0058695	£ 121,399	
	2010		LP cheek		£ 767	0.076	0.364	0.1	0.0027664		
			Valve cost		£ 1,763	Cost including valves & assembly				**£ 172,987**	**£ 24,712.46**
	2010		SPR ram main		£ 992	0.305	0.23	0.364	0.0255346		
D *	2010	P2-002	FSV Cheek	Quote	£ 271	0.129	0.364	0.125	0.0058695	£ 43,018	
	2010		LP cheek		£ 207	0.076	0.364	0.1	0.0027664		
			Valve cost		£ 1,763	Cost including valves & assembly				£ 94,605	**£ 13,515.04**
	2010		SPR ram main			0.305	0.23	0.364	0.0255346		
E	2010	P2-002	FSV Cheek	Supplied cost	£ 5,700	0.129	0.364	0.125	0.0058695	**£ 166,811**	**£ 24,636**
	2010		LP cheek			0.076	0.364	0.1	0.0027664		

* *B* and *D* would not quote for small quantities (16 off) and reflect volume prices.

Figure 5: P2-002 Ram manifold cost/volume analysis

2.1.3 CONTROL AND INSTRUMENTATION

The primary function of the cylinder control and instrumentation (C&I) is to control the set of valves housed in the ram manifolds that control the flow of fluid between the hydraulic cylinders, the accumulator and reservoir. The C&I consists of the following elements for the type of ram described in Section 3.1

- Seal sensors
- Control card
- Manifold sensor
- Packaging (Enclosure and support structure)
- Wiring

It should be noted that the cost of the remote central controller that reads and writes command to the individual ram cards is not included in ram manifold C&I. It is assumed that this controller is also required for the control of the motor/generator system and is therefore included with in the secondary system PTO cost metrics. The figures below provide illustrations of the control card and support structure.

For the purpose of providing a cost metric for the control and instrumentation it is not useful to provide this as a function of £/kW as it will generally remain constant for each ram, given the type and number of components required will generally remain the same for cylinder designs larger than those for the P2. The dominant cost element is the ram control card at 38% this is over a third of the total control and instrumentation cost for the ram.

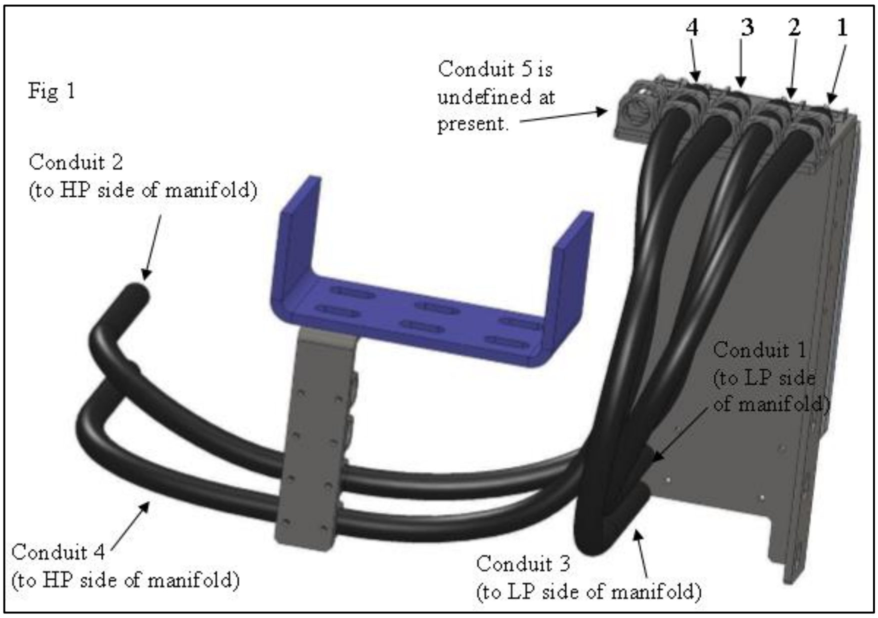

Figure 7: Ram Control card cable support structure

Figure 8: Ram Control Card & Enclosure

The table below provides the actual cost for components based on the P2 cylinder.

Component	Cost	%
Seal Sensors	£240	12%
Control Card	£750	38%
Manifold sensors	£240	12%
Packaging	£300	15%
Wiring	£430	22%
Total	**£1,960**	**100.0%**

Table 7: Cost Breakdown for Ram Control Components

2.2 ROD END BEARING

The REB perhaps could be considered as part of the hydraulic cylinder assembly as it is necessary for it to function as intended but costs and metrics are treated separately as bearing assemblies are likely to be fundamental to many different primary transmissions. In the case of the Pelamis P2 WEC the REBs were external to the machine and so each unit was sealed inside a flexible bellow which prevented water ingress or egress of lubrication to the environment.

Articulation at the Pelamis joint required two degrees of freedom. PWP developed two competing REB solutions. One based on rolling element bearings (deployed on the P2-001) and the other based on maintenance free plain bearings (deployed on the P2-002). On paper both solutions meet the requirements to provide sufficient articulation and resist the same design loads and while the rolling element solution costs substantially more it potentially offers greater wear life. Further research and testing is required before rolling element bearings can be proven to work in these regimes but early sign from P2 testing were promising so cost metrics for both variants are provided.

Which technology is best suited depends on the application and the planned operations and maintenance strategy e.g. frequency of intervention and cost of replacement or service.

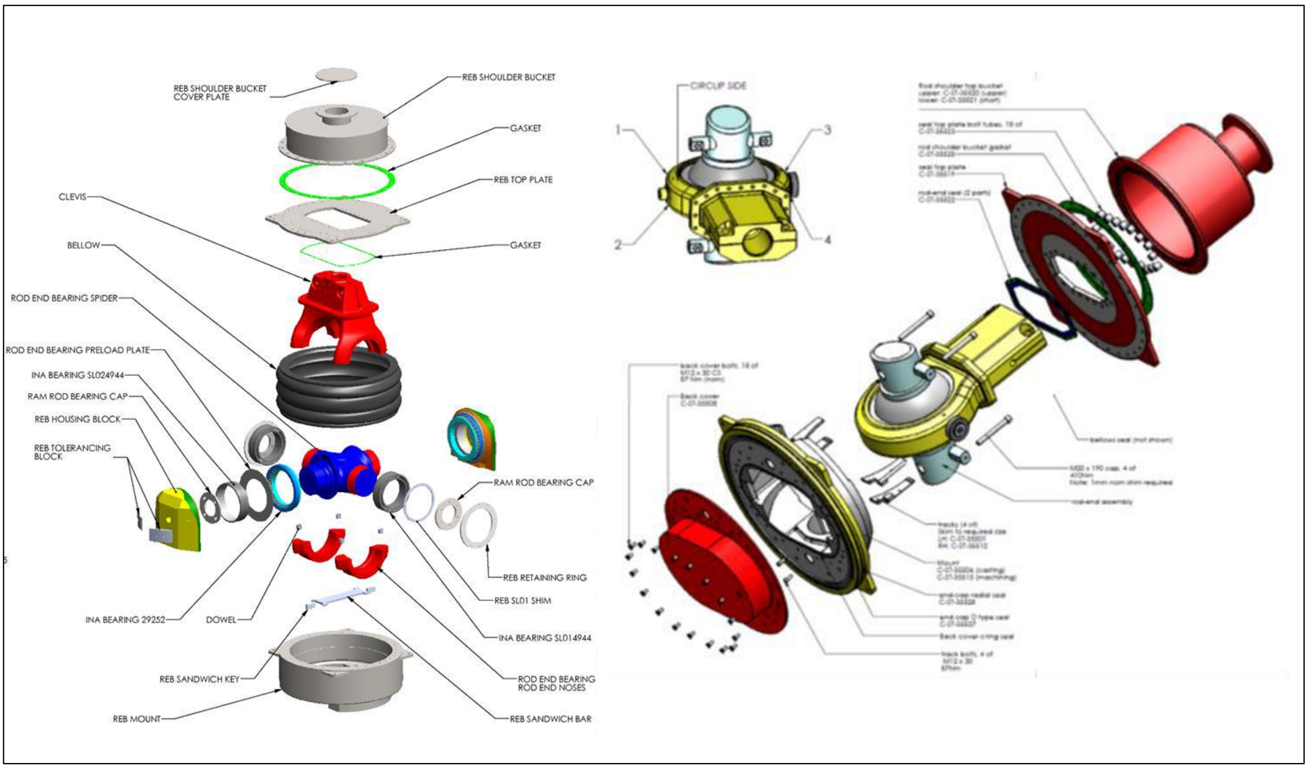

Figure 9 : Rolling element (left) and Maintenance free plain (right) REB designs

Figure 10 : P2-001 (left) and P2-002 (right) rod end bearing

Table 8 details the costs and proportions of the three major aspects of the REB assemblies: the housings, the bearings and the environmental protection.

	P2-001 REB (rolling)		**P2-002 REB (plain)**	
Bearing elements	£5,000	20.9%	£4,300	18.1%
Flexible seal	£2,500	10.6%	£2,500	10.6%
Mounts and housings	£16,300	68.5%	£9,600	40.2%
Total	**£23,800**		**£16,400**	

Table 8 : Bearing high level components

Parameter	Value	Comment
Articulation range	+/- ~30 degrees (conical)	Typical angles in service ~ +/-10 degrees.
Load rating	~1.8MN	
Weight	2,200kg / 1,200kg	P2-001 / P2-002
Calculated life		
P2-001	**Unconfirmed** **1yr – infinite life**	Very little data for this type of operating regime. Schaeffler/PWP started a program to investigate further as looked more promising than P2-002 type.
P2-002	2-4 yrs	Unfavorable conditions for this type of bearing.

Table 9: Key specifications for REB

Table 3 in section 2.1 details some of the key cylinder specifications which was the driver for these designs. This data may be used in conjunction with Table 9: Key specifications for REB, above as a basis for metrics or comparisons other than those detailed in Table 10.

	P2-001 (rolling)	P2-002 (plain)
£ /kg assembly	£10.80	£13.70
£/kg bearings only	£41.70	£23.90

Table 10 : REB metrics

3. ENERGY STORAGE SYSEMS

Hydraulic accumulators with gas backup bottles store energy between individual waves and wave groups to smooth the generated electrical output. The pre-charge pressure and volume of gas of each accumulator determines the Pressure Volume (PV) energy storage curve, with a combination of pre-charge pressures and gas volumes giving a more linear PV curve across the operating pressure range. The total cost is dominated by the piston accumulators themselves, and the high pressure bottles that provide the gas volume to utilise the full stroke of the accumulators. The use of multiple vessels is cost effective and offers redundancy in service, while also giving very good design flexibility and scalability.

The energy storage system also includes the reservoir system. These volumes hold the hydraulic fluid at low pressure when it is not storing energy in the accumulators at high pressure. As energy is absorbed, hydraulic fluid is transferred from the low pressure reservoirs to the high pressure accumulators. As for the accumulator system, the cost of the reservoir system is dominated by the cost of the reservoir vessels themselves and the use multiple vessels is most cost effective and offers redundancy in service, while also giving design flexibility and scalability.

The cost of the hydraulic fluid and nitrogen gas is also considered in this section. Together, the accumulator system, the reservoir system, and the hydraulic oil and Nitrogen gas make up energy storage system. The overall cost breakdown for the energy storage system is shown below. A more detailed discussion into the cost metrics and scalability of individual classes of component is then included.

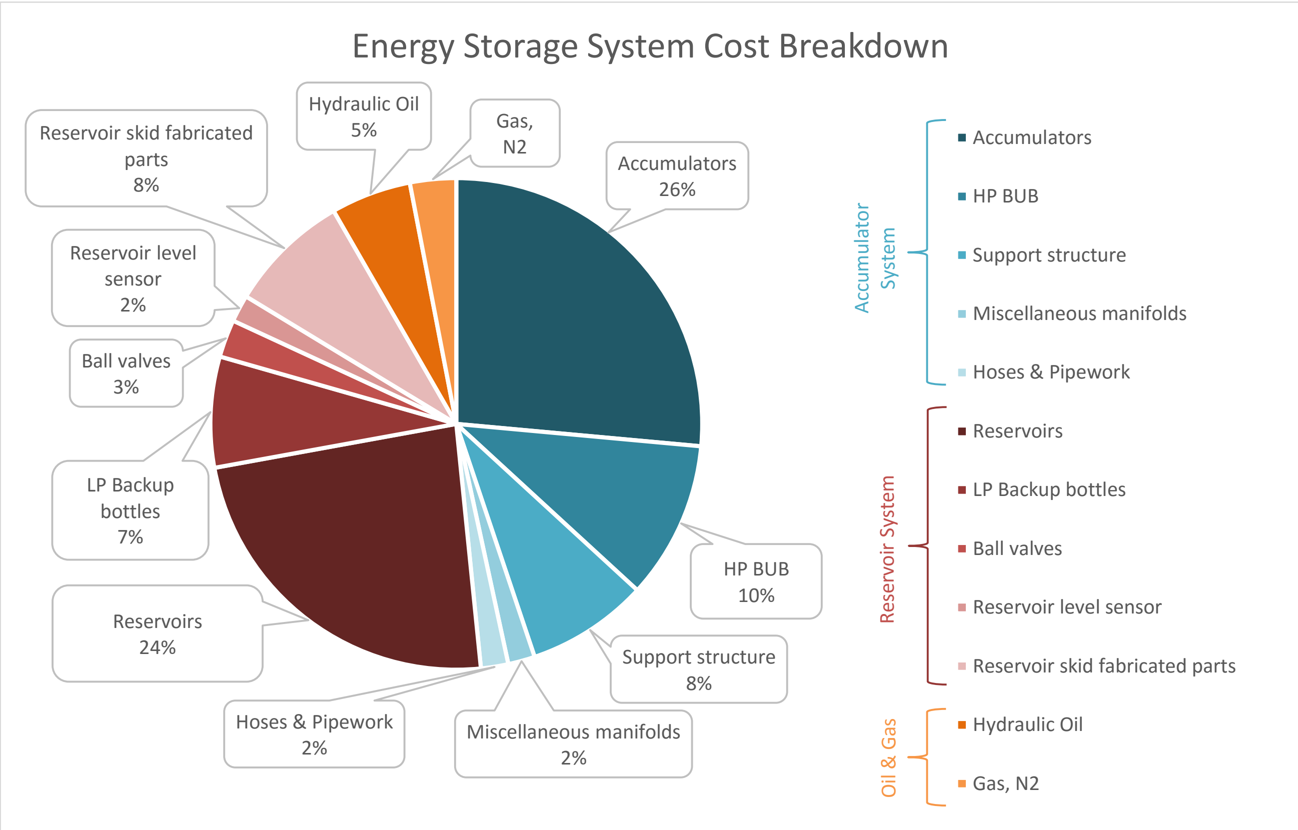

Figure 11 Hydraulic accumulators and HP back up bottles in P2-001

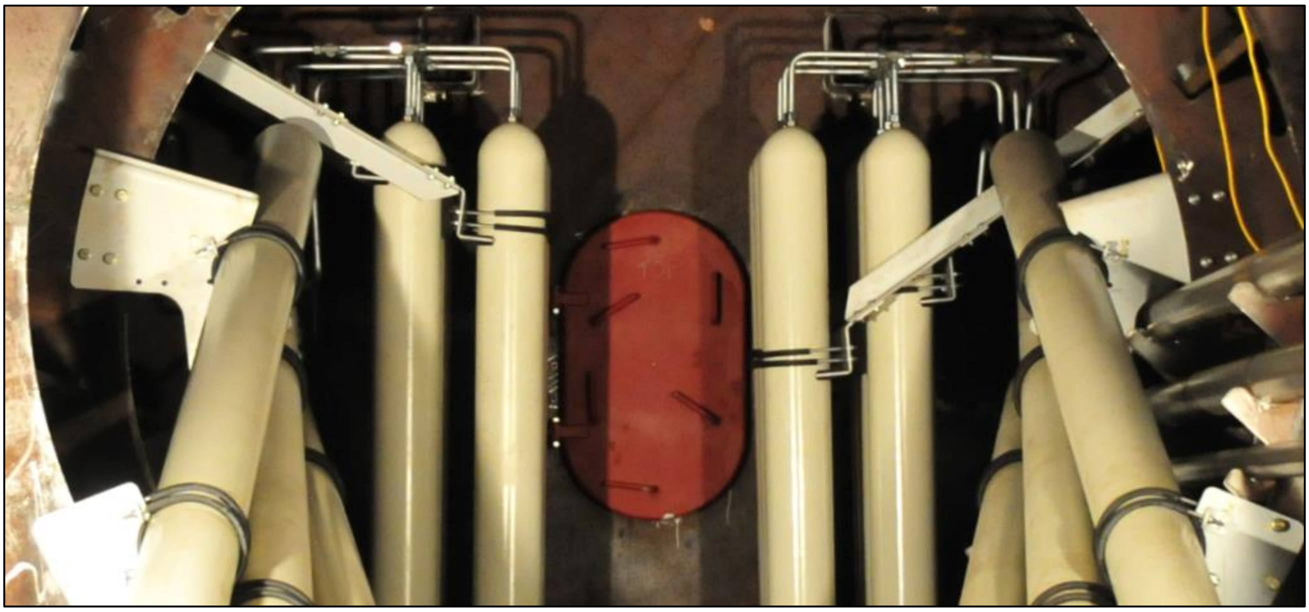

Figure 12: Percentage contribution of component to the overall energy storage cost (based on P2 costs)

3.1 ACCUMULATORS

Piston accumulators are used as the primary energy storage in the Pelamis WEC. The accumulators used in the P2 machines use standard diameters of roller burnished steel tubes for the main section with threads cut in each end for the end-caps and a sealed piston to separate the gas from the oil. The piston, end caps and the machining of the threads make up a large portion of the cost of the accumulator. In order to reduce the cost per litre of storage, the P2 accumulators were manufactured from standard mill lengths of tube with minimum cut-off to give the maximum volume with minimum (expensive) machining and extra components.

The most cost effective accumulator vessel size is determined by stock materials and the capability of manufacturing plant. This has been in the region of 200mm bore but this may vary with market conditions. The maximum length of accumulator vessel dictates the ratio of volume to expensive machining operations, so the longer the better. PWP minimised accumulator costs in the P2 machines by using the longest accumulators possible at the time. This is still thought to be the longest available.

The cost metrics derived for the accumulators based on the P2 PTO are as follows.

Metric	Value
Total Volume	160L (per accumulator, 960L of accumulation per PTO)
Total weight	565kg (per accumulator)
Total Cost	£2,900 (per accumulator)
Cost/L	£18
Cost/kg	£5

Table 11: Accumulator cost metrics

Scalability of energy storage can readily come from simply adding or removing vessels. For example, the P2 machine made use of 3 accumulator vessels each at different pre-charges, also providing a linearized relationship between stored energy and pressure. Additional vessels are most cost effective when added at higher pre-charges and with larger gas back-up volumes, although some shifting of the pre-charges would be required to best manage the variability of absorption across the power range. This allows the above metric to be applied broadly in proportion to increases in energy storage requirement, which in turn is broadly proportional to power absorption.

3.1.1 ACCUMULATOR BACK-UP BOTTLES

Standard forged gas cylinders are used for the high pressure gas back up volume, these are mass produced and less expensive than equivalent machined vessels. The costs and associated cost metrics for these Back-Up-Bottles (BUBs) are:

Metric	Value
Total Volume	75L (per BUB, 1050L of BUB capacity per PTO)
Total weight	135kg (per BUB)
Total Cost	£490 (per BUB)
Cost/L	£6.50/L
Cost/kg	£3.60/kg

Table 12: High pressure back-up volume cost metrics

Discussion with suppliers and their subsequent efforts have uncovered an additional range of forged high-pressure back-up-bottles with larger volumes. 75lt, 150lt, 300lt bottles are available with similar cost per litre adding additional confidence to the figures calculated above. As for the piston accumulators, scalability therefore comes with increasing the number and volume of vessels. Using larger individual gas storage vessels reduces the number of pipes and fittings while the larger vessels have a very similar specific cost per litre. There is therefore good flexibility in the final choices here to achieve a given volume of storage matched to the accumulator vessels and selected pre-charges.

In terms of the BUB requirements with increased accumulation capacity, the required volume of the BUBs does not scale directly with the increase in accumulation. A greater number of BUBs is required for accumulation at higher pressures than lower pressures therefore the ratio of BUB volume to accumulation volume does not remain consistent as the PTO power output is scaled up. As such, the cost of the BUBc cannot be directly included as a proportion of accumulator cost but must, instead be calculated separately.

3.1.2 GAS CONNECTIONS & STRUCTURE

The accumulator and gas bottles are connected by a rigid metal pipe, as the system holds a static mass of gas at high pressure, flexible hoses (air or hydraulic) are permeable and should not be used. The cost of piping the gas bottles is a function of the number of bottles therefore small savings may be made using fewer larger bottles but this does not significantly affect the cost metrics given above. More importantly, additional bottles give advantages in reliability and assembly.

Additionally, the accumulators have associated necessary manifolds and support structure. The costs of these components for the P2 PTOs are summarised in Figure 13.

Component	Cost
Gas pipework	£450
Support structure	£5,300
Manifolds	£1,150
Hoses & fittings	£750
Total	**£7650**

Table 13: Accumulation connection and support structure metrics

This adds an additional £8 per litre of accumulation (an additional 44% of the individual accumulator cost) onto the cost of the accumulator system.

3.1.3 ACCUMULATOR SYSTEM COST SUMMARY

The breakdown of costs for the accumulator system are as illustrated below. It can be easily seen that the accumulators and BUBs dominate the costs. They account for 76% of the overall costs with the costs of integrating them into the overall system addition an additional 32% to the cost of the system.

Given the differences in £/L metrics for the accumulator and BUB and the fact that that volume requirement for BUBs does not directly scale with accumulation volume requirement it has been decided to keep these two metrics separate in any further calculations. However, the cost of the ancillary items has been calculated for different volumes of accumulation and remains broadly similar throughout. The following summary cost metrics can therefore be derived.

Component	Cost Metric (integrated system)	Comment
Accumulator	£26/L	Accumulator cost + cost of ancillary items
HP BUB	£6.50/L	

Table 14: Accumulation metrics summary

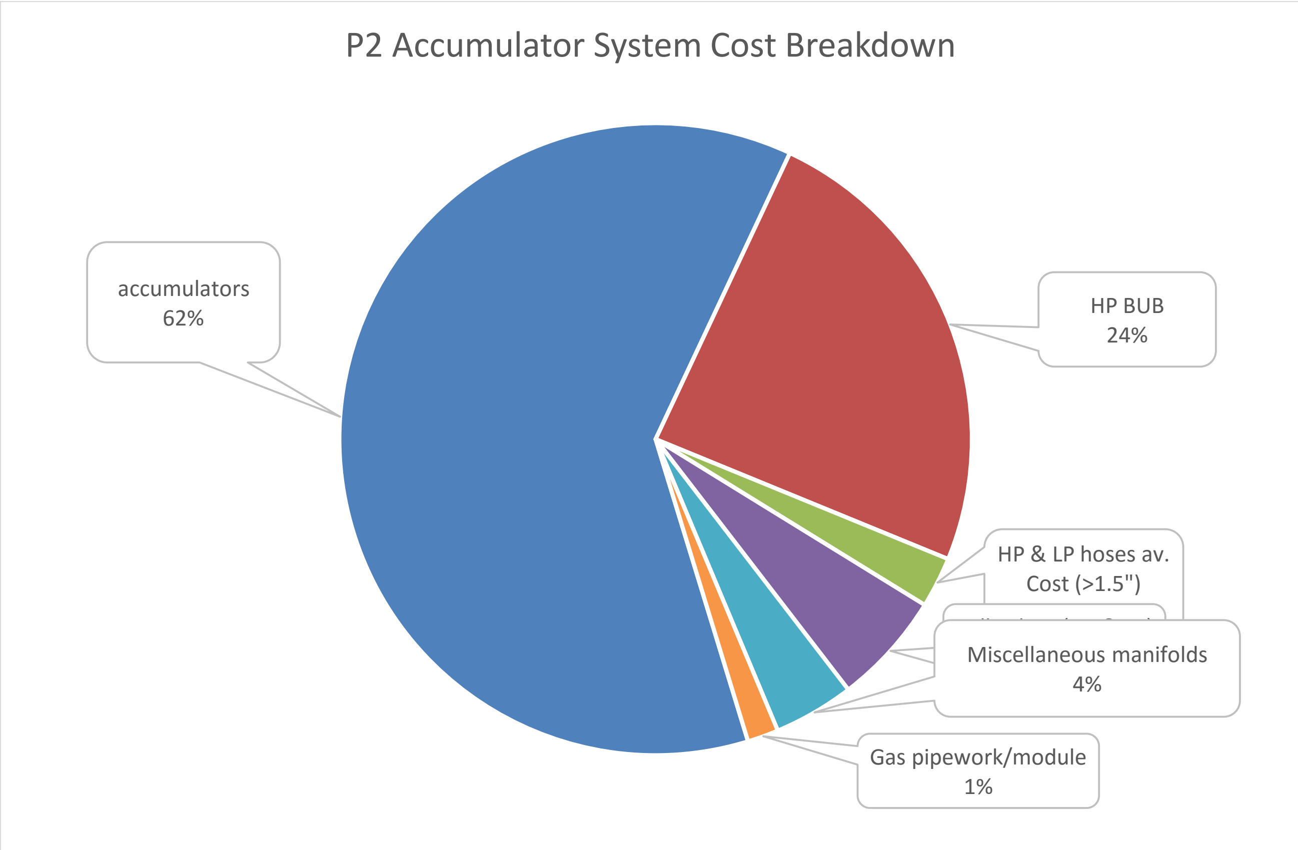

Figure 13: Cost breakdown for the P2 accumulator system

N.B a previous version of this chart was shown in the PTO deliverable 5 (revision C1). As part of the work done to complete this deliverable some of the numbers utilised to create the original chart have been shown to be incorrect. The chart above represents the correct breakdown. This chart will be updated for later revisions of the deliverable 5 report.

3.2 RESERVOIRS

The hydraulic fluid reservoir holds the hydraulic fluid at low pressure when it is not storing energy at high pressure. As energy is absorbed the hydraulic cylinders transfer fluid from the low pressure reservoirs to the high pressure accumulators. The reservoirs must therefore be sized to hold sufficient fluid to fill the accumulators as a minimum. The reservoirs also include an excess of hydraulic fluid to accommodate volume changes from cylinder extension and retraction, accommodate vessel motion and rotation, and also to avoid any slow leak that may develop during operation from preventing normal operation for extended periods.

This implies that, as for the accumulators, the reservoirs scale in volume in proportion to the energy storage requirements.

Note that the Pelamis PTO uses a sealed and pressure boosted hydraulic system, this is to prevent oil cavitation when the rams are inducting and to prevent the ingress of moisture into the system without the need for boosting sub-systems and associated parasitic loss. As the whole system is pressurised to a static boost, the reservoir and backup bottles are classed as pressure vessels and need to adhere to certain design codes. This heavily influences the relationship between vessel shape, size, and cost. The P2 reservoirs were pressurised to 4bar and were rated to a working pressure of 10bar, with a 15bar test pressure.

Metric	Value
Total Volume	1200L per reservoir (2400L per PTO)
Total weight	800kg (per reservoir)
Total Cost	£7,825 (per reservoir)
Cost/L	£6.50/L
Cost/kg	£9.80/kg

Table 15: Reservoir metrics

Additional volume of low pressure reservoirs and gas back-up vessels is achieved with minimal cost increase through additional vessel length. This reaches a breakpoint at around 1800lt for the P2 reservoirs corresponding to the largest single rolled plate size. This increase was selected for the P3 design resulting in a slightly lower cost/litre than for the P2 reservoirs but still close with that quoted above.

Increased length may still be a cost effective route beyond this size but larger fluid flows and associated connections to the reservoir would be likely to require additional services on the bottom flange, with would in turn require greater diameter. A good solution to allow greater energy storage is likely to involve additional reservoir vessels of similar size to the P2, also offering the potential for greater fault tolerance, with additional split points in the circuit. Example system configurations of larger capacity systems have been specified in section 7.

3.2.1 RESERVOIR BACK-UP BOTTLES

The reservoir back up bottles are connected to the top of the reservoir and provide an additional gas volume to reduce the low pressure variation in the system as the oil volume changes. As the reservoir back up bottles do not contain liquid, they fall under different, less stringent, air receiver design codes than the reservoirs and are internally painted rather than nickel plated so have a lower cost per litre. This only holds true however, if the ratio of BUB volume to reservoir volume is maintained as the system is scaled. The ratio of BUB volume to reservoir volume therefore needs to be maintained at 1.25 as the system capacity is increased. Due to this static ratio the cost of the BUBs can also be defined as a cost/L of reservoir volume (also included in the table below).

Metric	Value
Total Volume	1500L per circuit (3000L per PTO)
Total weight	430kg (per circuit)
Total Cost	£2,400 (per circuit)
Cost/L (BUB capacity)	£1.60/L
Cost/L (reservoir capacity)	£2.00/L
Cost/kg	£5.60/kg

Table 16: Reservoir back up bottle metrics

3.2.2 RESERVOIR SYSTEM COST SUMMARY

The reservoir system also needs to include ancillary items such as valves, sensors and mounting bracketry. The cost of the main PTO skid fabrication is also predominantly a result of the requirement for reservoir support as these are the largest component housed on this structure. The electrical cabinets and integrated MG sets are then hung of this frame but this adds little extra cost. As such the cost of the PTO frame should also be included in the reservoir costs. The cost of all the ancillary items for the reservoir system for the P2 machines totalled £8,100. This adds an additional £3.40 to the cost per litre of the reservoir system.

A summary of all the costs associated with the reservoir system is given in the table below. This shows that the reservoir system can be costed using a simple cost metric of £11.90/L of reservoir volume. The percentage breakdown of costs for the system is shown in the pie chart after.

Component	Cost/L (reservoir vol.)
Reservoirs	£6.50
BUBs	£2.00
Ancillary Items	£3.40
Total Cost/L	**£11.90**

Table 17: Reservoir metrics summary

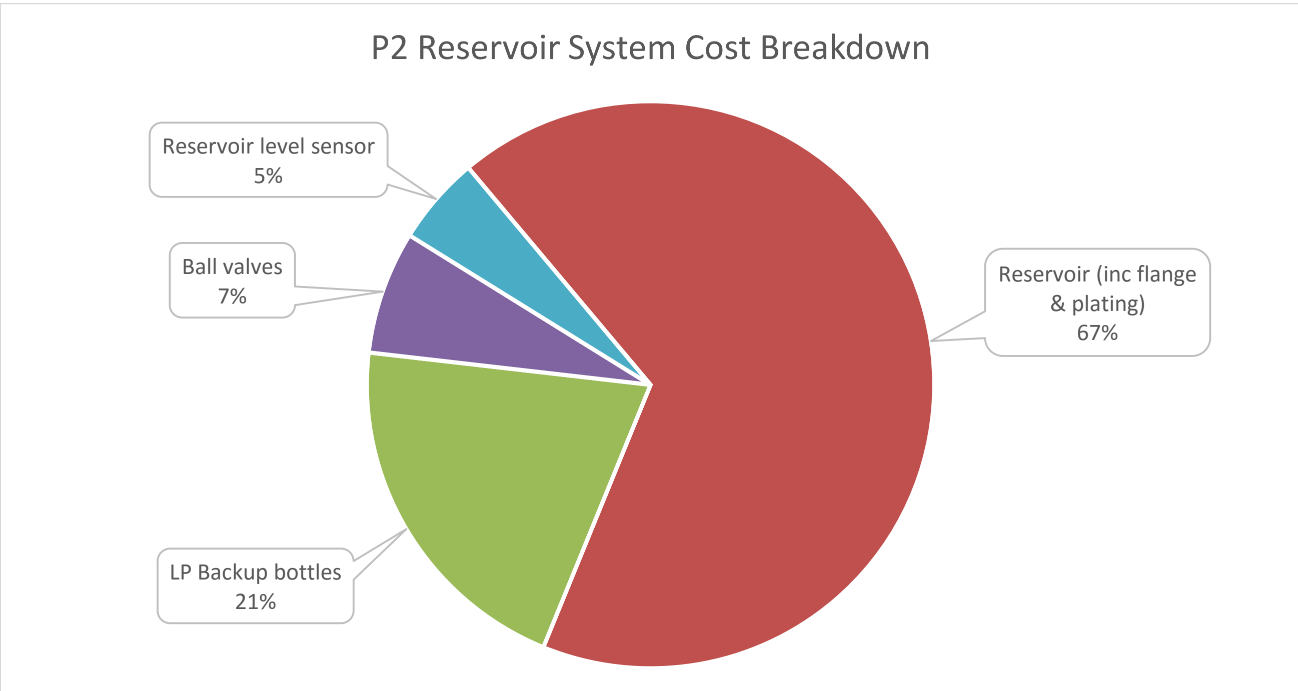

Figure 14: Reservoir system cost breakdown

3.3 HYDRAULIC FLUID & NITROGEN GAS

The volume of fluid required scales with the energy storage volume, and hence with the rated power. The P2 Pelamis devices included 2000L of premium grade hydraulic oil per PTO. The cost of this was ~£1.75/L.

The quantity of gas used to pre-charge the accumulators and reservoirs also scales similarly but the cost of gas is harder to quantify due to the way in which it is supplied. High pressure nitrogen gas is supplied in MCPs (Manifold Cylinder Pallets) in which the cost of the gas, delivery and hire of the pallet of gas bottles is separate. This means that the cost of the gas not only depends on the volume but also on assembly and commissioning time. However, the cost is relatively insignificant compared to the overall cost of the PTO so an estimated cost for the P2 PTOs of £2000 has been used in this analysis. This value is based on actual costs and is scaled according to oil volume scaling for the example system costings given in section 7.

4. SECONDARY PTO TRANSMISSION AND ANCLILLIARY SYSTEMS

For the purposes of this study, the secondary transmission includes:

- Hydraulic motors
- Main manifolds
- Filtration systems
- Temperature regulation and cooling system
- Ancillary hydraulic systems (pressure relief, bypass functions, sensors, protection systems etc.)
- Electrical generation and control
- LV switchgear
- Instrumentation

Although some of these systems are also necessary for operation of the primary transmission, these are housed on the single integrated PTO skid along with the generation systems and tend to scale with the rating of the secondary transmission (i.e. power rating of the WEC) independently of the characteristics and costs of the primary transmission.

For ease of analysis, components of the secondary PTO transmission have been categorised according to the dominant engineering discipline applicable to those components, either hydraulic or electrical & control. This distinction has been made in the section headings below. A general overview of the cost contributors to the P2 secondary transmission is illustrated in the pie chart in.

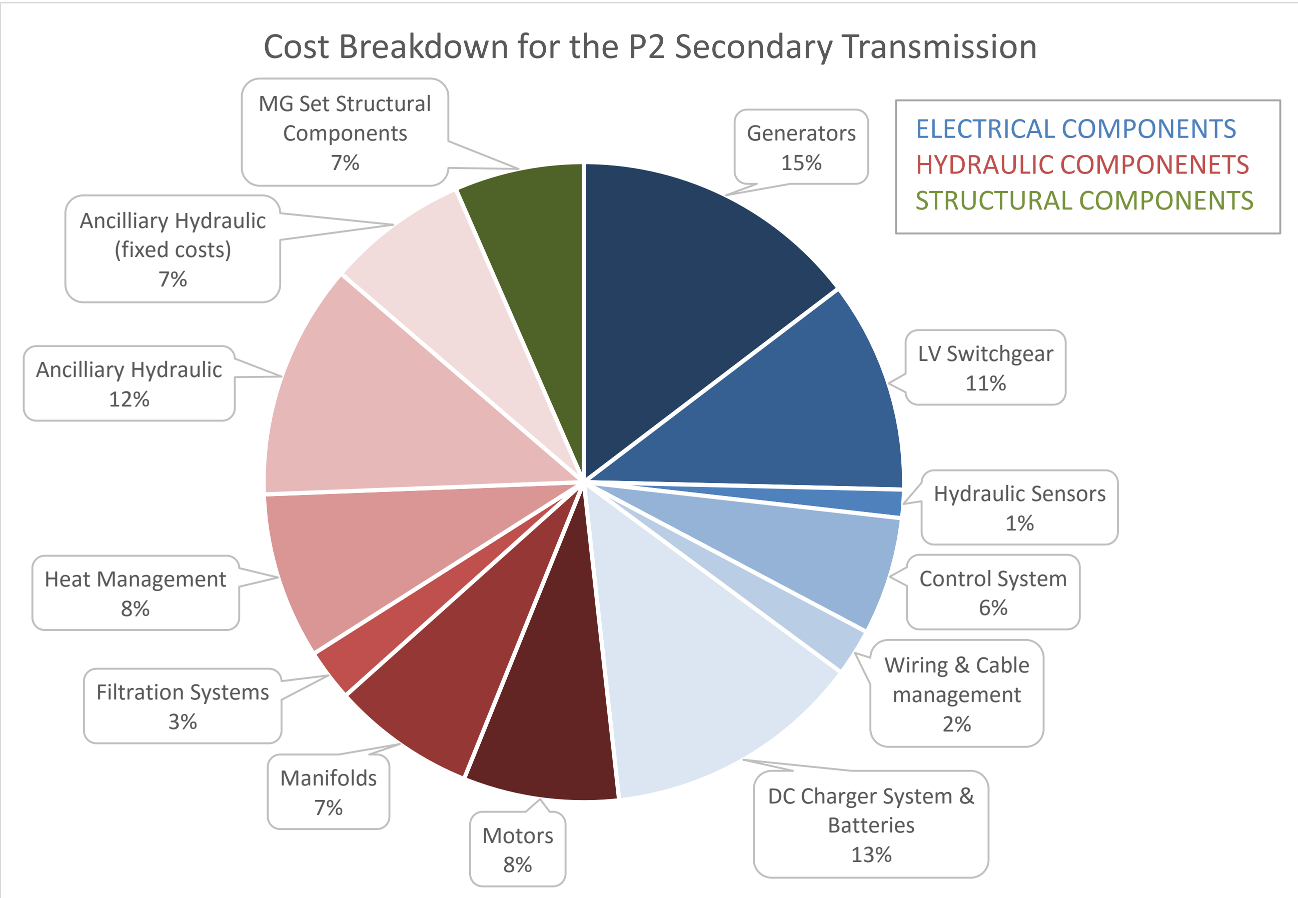

Figure 15: Secondary transmission cost breakdown (based on P2 system)

4.1 HYDRAULIC SYSTEM

4.1.1 MOTORS

High efficiency variable displacement bent axis motors of three sizes have been considered in this analysis.

- Parker V12-60, 80kW @ 1500rpm, used in the P2 machines
- Parker V14-160, 125kW @ 1500rpm, used in the P1 and P2 machines
- Danfoss H1-250, 185kW @ 1500rpm quoted for use in the 435kW machine

Each motor cost is considered including an integrated displacement feedback sensor developed and retrofitted by PWP. From the known costs of these motors a fairly consistent cost metric of ~£30/cc (+/- 10%) for motors of this type (>160cc/rev) can be derived. This simple metric enables the cost of larger motors to be estimated. Utilising motors of different sizes means the secondary transmission system can be built up using different combinations of motor up to the required rating, while also providing optimal part load efficiency and fault tolerance. Although Parker and Danfoss do not supply the larger motors required for higher output PTOs, Rexroth do. The price of their 315cc/rev (~250kW @ 1500rpm), has been extrapolated based on £/cc displacement cost from V14 and H1-250 quoted costs.

The motor costs can be summarised as follows. A smaller 60cc/rev unit has also been included in this table as it was utilised as part of the P2 design to ensure part-load efficiency. This motor does not conform to the above metric but it is unlikely that such a small motor would be used in any scaled up PTO design. Indeed, it was not planned to use such a motor in the P3.

Motor Displacement	Cost	Cost/cc
60cc/rec	£2,850	£48/cc
110cc/rev	£3,800	£35/cc
160cc/rev	£4,270	£27/cc
250cc/rev	£7,420	£30/cc
355cc/rev (estimated cost)	£10,650	£30/cc

Table 18: Bent axis variable displacement hydraulic motor metrics (2014prices)

4.1.2 MAIN MANIFOLDS

These manifolds control the oil flow to the motors, handle the filtration, temperature, offline flow control, pressure control and other auxiliary functions. As detailed in the cost analysis for the ram manifolds (section 2.1.2), large densely populated manifolds prices are fairly consistent with respect to cost/tonne or cost/m^3. These cost metrics of £180k/m^3 and £26.5k/tonne also apply to the secondary transmission main manifolds.

The main manifolds increase in size (or number) as the number or capacity of motor/generators increases. It is difficult to predict exact size or weight of the manifolds required for a specific system based on its output rating. However, based on P2 main manifold prices and quotes for P3 main manifolds cost contributions for differently rated motor displacements have been estimated for the cost predictions in section 7. These values are estimates only based on engineering experience and judgement and there is a high degree of uncertainty in the values for larger manifolds.

Ideally a single manifold for each of the HP and LP functions would be used to house all of the hydraulic services for the entire PTO although this is increasingly difficult as ratings increase. The quoted P3 manifold represents a manifold on the limits of production capability hence separate manifolds may be required for large PTO systems. This may increase costs further.

4.1.3 FILTRATION SYSTEMS

All hydraulic systems produce contamination as part of their normal operation so all, or a portion of the oil needs to be filtered in all modes of operation. Filtration systems vary widely in cost and effectiveness and it was PWP's experience that the benefits (system reliability and efficiency) of a good filtration system far outweigh the costs of providing one. The costs given below are therefore for the relatively expensive filtration system that PWP deemed necessary in an application of this type.

There are three independent filtration systems with an option for a fourth designed into the Pelamis P2 PTO. These are:

1. Primary filtration – this is in the motor flow paths providing filtration for all oil flowing through the PTO system except leakage, limited by the peak flow of the motors. The pressure drop through the filter directly impacts on the efficiency and economics of the .machine so larger filter housings much than recommended by the manufacturer were specified to reduce the pressure drop on a cost-benefit basis.
2. Offline filtration – this filter is downstream of the motor bypass valve and is used when the motors are not running. As this does not cause any additional losses to generation it is sized according to the manufacturer's recommendation.
3. Pilot filtration – a small filter housing is used to give additional fine filtration to the oil supplied to the pilot control circuit
4. Optional kidney loop filtration – low flow ultra-fine filtration to prevent accumulation of very fine particulate contamination

There is no simple metric for the cost of the filtration with the size and rating of the PTO. The overall costs attributed to filtration in a P2 PTO, was ~£1300 (or £650 per motor/generator circuit). These value and engineering judgements have been used to derive explicit values for filtration costs in the example systems illustrated in section 7.

In addition to the filtration system above, each PTO includes a single contamination sensor at a cost of ~£900.

In terms of scalability, broadly speaking, the greatest sources of contamination are the cylinders, resulting in an increased requirement for filter capacity in proportion to the overall cylinder stroke, this increase is, however, hard to define. The sizing of the primary filters specifically is determined in order to minimise flow losses (increase efficiency). Therefore, the size of these filters also increases with increased rating of the secondary transmission.

4.1.4 HEAT MANAGEMENT

The heat exchangers are based on standard "box coolers" used to cool ships systems. The Pelamis design also included temperature regulation valves and leak protection valves. In addition, impressed current copper anti-fouling is required to prevent marine growth on the heat exchangers to ensure their efficiency is maintained throughout their life. A structural penetration and 'sea-chest' feature is also required on the main structure but the cost of this is not treated here due to the uncertainties surrounding this in alternate structural arrangements.

The best priced heat exchangers that PWP were able to find cost ~£20/kW of heat dissipation. This heat rejection capability is calculated assuming minimum water flow, a maximum oil temperature of 60°C, and a sea-water temperature of 10°C.

The heat rejection system must be sized to reject as heat, all of the absorbed energy across all conditions, to deal with any potential grid failure and loss of mains power export. This makes the coolers scale with respect to required kW heat rejection rating, similar to the secondary transmission ratings. The coolers increase in size as a function of the length and number of tube bundles. The resulting increase in cost with power rating of the secondary transmission is therefore broadly linear.

The anti-fouling system requirements are more a function of the sea-chest size than the output power rating. This will be hugely affected by the design of the WEC. However, it is very likely that the sea-chest size will increase as heat exchanger dissipation requirement increases. It has therefore been assumed in section 7 that anti fouling costs increases proportionally to the increase in heat exchanger dissipation required. This is a rough estimate but, given the relatively low cost of the anti-fouling system within the PTO is a reasonable assumption. The cost increase allows for the additional copper that would be required in such systems. The P2 antifouling system cost £1,100 per PTO and for a heat exchanger rated for 300kW of heat dissipation and therefore adds an additional £4/kW of heat dissipation to the cost of the heat exchanger system. This brings the total cost for the heat exchanger system to £24/kW of heat dissipation required.

Figure 16: P2 heat exchanger and their associated anti0fouling copper anodes (marine growth is on the edge of acceptable level and duty-cycle of anti-fouling system was subsequently increased to improve anti-fouling characteristics)

4.1.5 SECONDARY AND ANCILLIARY HYDRAULIC EQUIPMENT

Ancillary equipment includes the connecting hoses, pipework, clamps, ball valves, and the auxiliary pump/charger as well as pressure regulation and safety systems. A number of these components, most notably the auxiliary pump and the alternator, do not been scaled with the rest of the system. In the auxiliary pump/alternator example, it is sized to provide a back-up power supply for the PTO control system and therefore is not related to the output of the PTO. The functional requirements of these component would remain the same regardless of the size of the PTO. As such, they have been classified as fixed cost ancillary hydraulic components and will contribute £6,000 to the cost of a PTO regardless of its output capacity.

There are many other relatively low cost hydraulic components that would, however, increase in cost as the flow requirements and output rating of the PTO was increased. Example costs for different sized hoses is given in Table 19 below. The larger LP hoses (2.5”) used to date have cost over twice that of their smaller, 2”, counterparts. Other types of hydraulic component would also increase in size and cost although there is no simple metric for scaling the cost of these components. The cost of these at different rated power outputs has thus been estimated explicitly, based on engineering judgement and experience, in the treatment in section 7. The total cost of these low cost items in the P2 PTO was £10,000.

Average large bore hose cost, SAE flange end fittings (2010)			
Description	**Avg. length (mm)**	**Avg. cost**	**Avg. cost/m**
LP, 2", 78 Bar	1867	£71	£40
LP, 2.5", ~50 Bar	1500	£153	£105
HP 2", 350Bar	2900	£153	£55
HP 1.5", 350Bar	3100	£125	£55

Table 19: Hose costs variations with size & pressure

4.2 MG SET STRUCTURE

The MG set structure supports the motors, generators, MG set electrical cabinets and motor manifolds. It is attached to the PTO skid structure (reservoir support structure) during PTO assembly. The MG structure fabricated parts for the P2 machine cost £5,500 to support 2 motor-generator units. This also included the motor bell-housing costs and other required bracketry and structure.

The main generator support structure for the P2 design was an efficient laser cut folded steel structure with a relatively low cost (the prototype and P1a MG structures were costly by comparison). Increased generator output requires increase real-estate to mount these components as frame size increases, this will increase complexity and relative cost. To estimate structural cost for PTOs of a larger output a very rough scaling factors relative to the P2 unit cost have been used to account for any increase in the number of generators and/or increase in generator size.

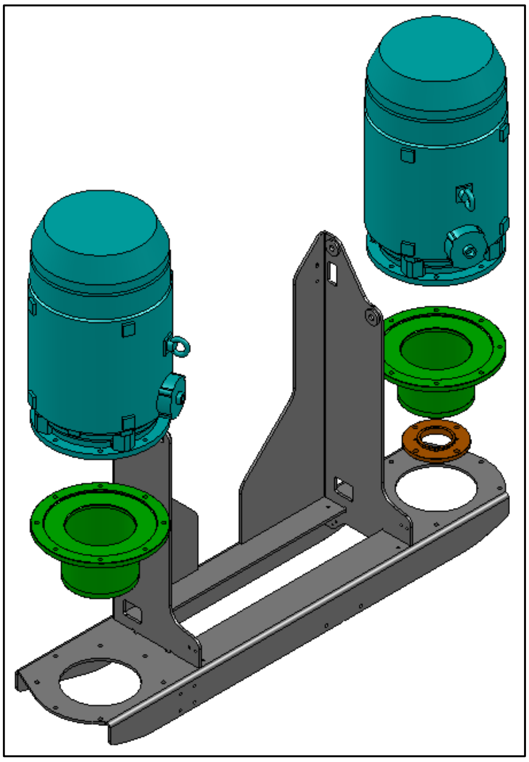

Figure 17: Illustration of main P2 PTO structural component (and generators fitting on to it. Additional bracketry was also required to mount MG set cabinet and other components.

4.3 ELECTRICAL AND CONTROL SYSTEM

For the purposes of this report, control and electrical system covers all equipment required for control and monitoring of the secondary hydraulic and electrical PTO system to the local point of connection on the 690Vac busbar. It is also assumed that a standard 3-phase 415Vac supply is provided as an auxiliary supply to the Motor Generator set. Section 5.1 discusses the requirement for conversion from the LV busbar connection to the MV connection at the wet-mate connector.

The Motor Generator set (MG set) in the P2 contains two induction generators, one rated at 125kW and a second rated at 80kW. A single enclosure located in between the two generators is used to house the control and electrical equipment associated the secondary PTO system. The illustration below shows the layout of the generators and electrical control enclosure in the final stage of assembly prior to mounting on the PTO skid.

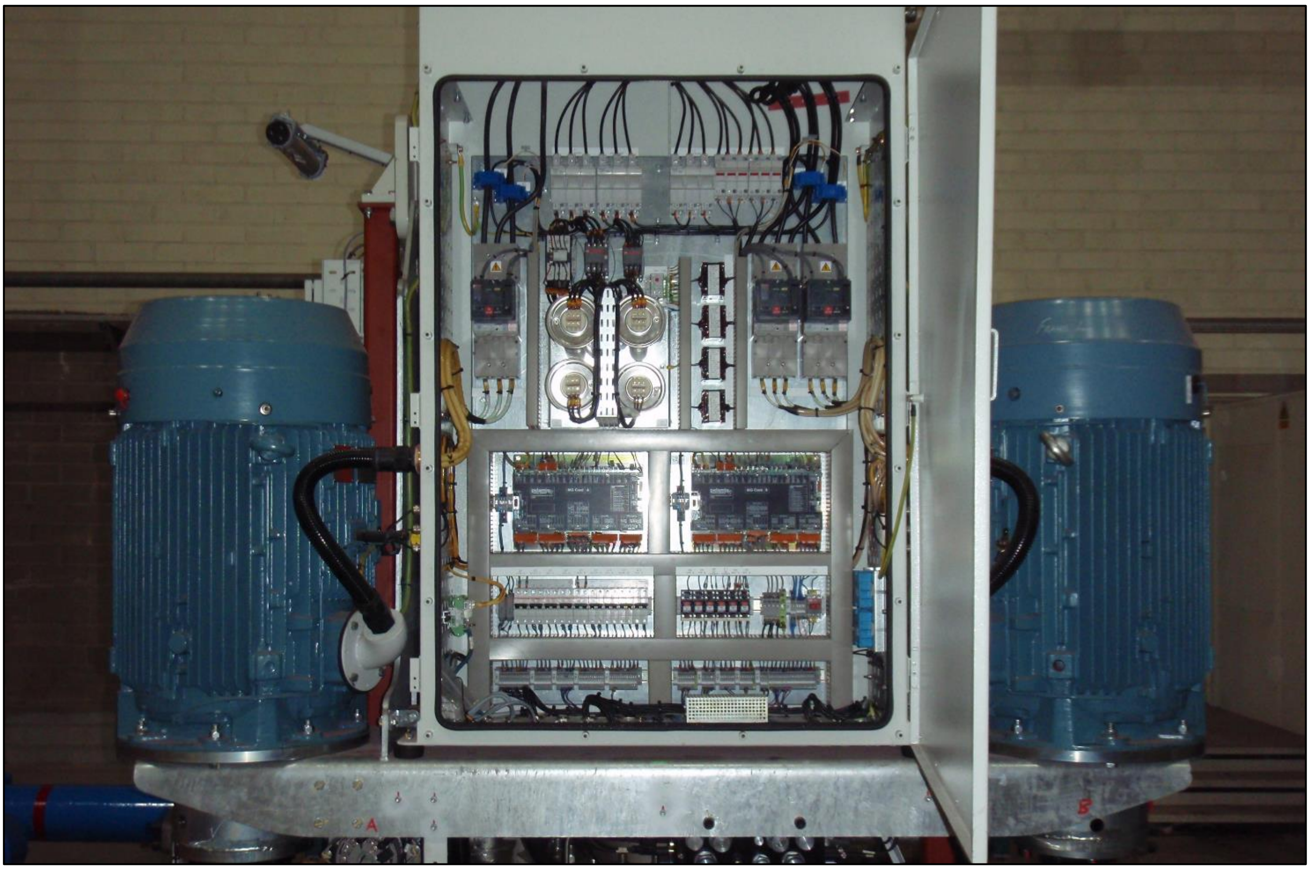

Figure 18: P2 Motor Generator set

The most appropriate cost metric to use for this system is cost/kW with the power rating is based on the nameplate rating of the associated generator. In the P2 PTO, the hydraulic system and motors that interface with generators are split into two separate services, circuit A and B. Each service can be broken down to the following system components.

- Generators
- LV Switchgear
- Instrumentation
- Control System
- Wiring
- DC Supply & Batteries

4.3.1 GENERATORS

The generators used in the P2 Pelamis were supplied by ABB, these were induction generators that use a frame and mechanical assembly from the standard commercial product range. Minor internal modifications were made by using low loss laminations and windings at relatively low cost of ~£1000, this cost increase would be more than offset by the increased yield over the lifetime of operation. The rating of the generators used on the P2 were 80kW and 125kW. Further cost data for different capacity rating of generators was provided by ABB, to illustrate the cost/kW of a standard high efficiency generator from a rating of 100kW to 1MW, this is shown in Figure 19.

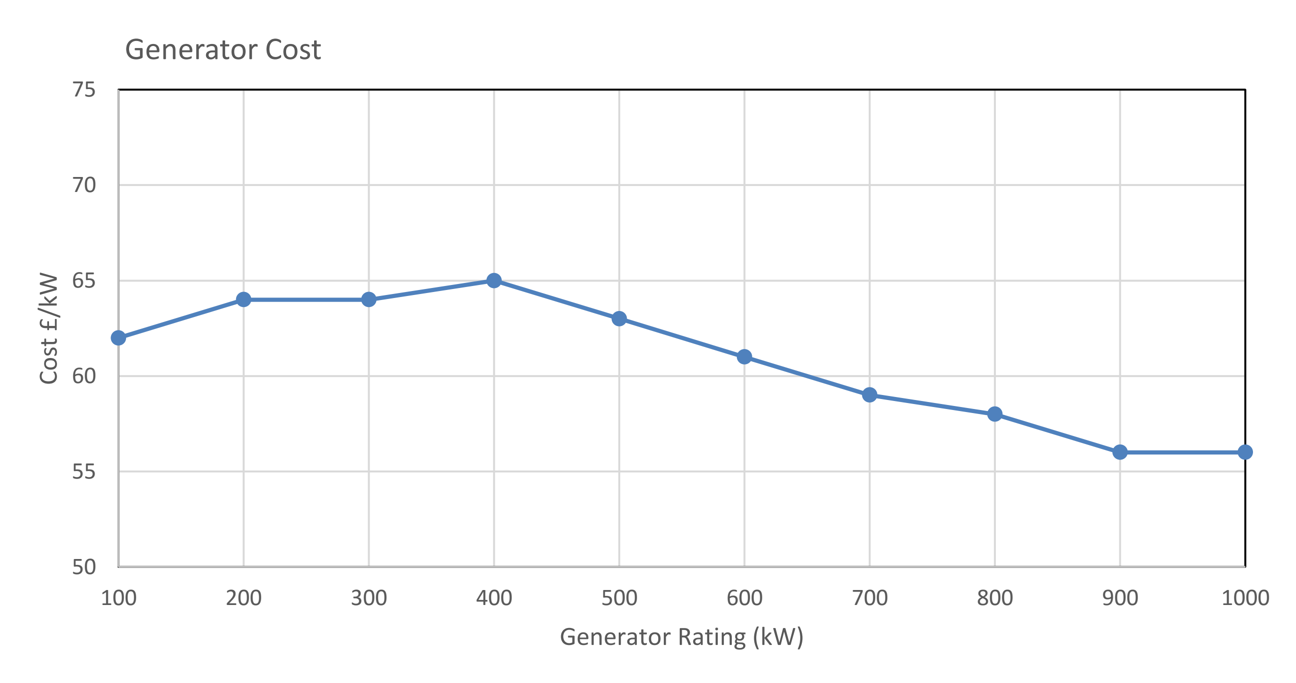

Figure 19: Generators Cost Metrics

The generator costs are all for generators of a similar efficiency level to those used in the P2 Pelamis. For the generators rated above 400kW the cost begins to decrease. This is because the inherent efficiency level of the standard generators rated above 400kW is equivalent to that of the smaller generators that have modified low loss lamination and copper windings incorporated. As such, the additional cost of the low loss windings is not required.

The cost variance over the power ratings illustrated is £9/kW. This data demonstrates is that irrespective of the of the rating and number of generators selected for a power take-off system of a specific rating, the total cost of the generators will not vary significantly. For example, generator costs for a 1MW system using a single 1MW generator would cost £56,000 and for 10 off – 100kW generators would be £62,000.

The above analysis indicated that a cost metric of £60/kW will give fairly accurate cost of generators within the levels of power output being considered. This would cover all combinations of different generator sizes in order to create the overall power rating required. It should be noted that the criteria for selecting the generators for the Pelamis PTO, was predominantly determined selecting the rating and number of generators that would provide the optimal conversion efficiency. This must be analysed with respect to the occurrence weighted power outputs in order to optimise efficiency properly.

4.3.2 LV SWITCHGEAR

The LV switchgear is contained in the enclosure located between the 2 generators in the P2 machine as shown in Figure 18. The main purpose of these components is for the start//stopping and protection of the generators and also the switching of the power factor correction. The cost element for the switchgear only shows a small increase against the increased size of generator, this because most components do not change with rating apart from the circuit protection and power factor correction. For the P2 PTO system the switchgear associated with each generator cost £4,500. It is estimated that for generators above 150kW electrical rating this would increase to £5,000 per generator.

4.3.3 INSTRUMENTATION

The majority of the instrumentation are pressure sensors that are used to monitor oil pressure in the high and low pressure systems and also gas pressure in the accumulators. There is redundancy incorporated at all points of pressure measurement within the hydraulic system and this redundancy has been taken into account in calculation of the costs below. The cost of pressure sensors can vary greatly dependant specification, the higher level of accuracy and reliability required, the greater the cost. Sensors were specified for the P2 machine according to minimum accuracy required. Given the relatively low cost of instrumentation compared with the overall cost of the PTO system it is fair to assume that the cost per generator remains fixed and is not affected by levels of accumulation or by the rating of the generator. Based on the P2 experience the cost of instrumentation is £600 per generator.

4.3.4 CONTROL SYSTEM

The control system requirements are based on a COTS B&R automation X20 system. This system was the latest generation of control system designed, procured and commissioned ready for installation into the P2 machines just prior to PWP administration. It is a modular system where input and output interface blocks are selected according to control and instrumentation requirements. Control for each individual generator is required but the control system costs remain fixed as they are not affected by the rating of the generator. For each generator included in a PTO system the control system costs are estimated as £2,500.

4.3.5 WIRING

The PTO wiring costs covers all cables required that run from the LV switchgear enclosure to instrumentation sensors and actuators as well as cable management requirement in order to properly route and support them. The cables used typically have moulded connections at the point of termination to the actuator or sensor, the type of cable must be resistant to hydraulic oil and water. Wiring costs estimated as £1000 per generator, these are fixed as they are not significantly affected by the rating of the generator.

4.3.6 DC SUPPLY & BATTERY BACK-UP

The DC supply system is required in order to power the module and MG control system and to allow valves to actuate etc. Batteries are also required so that control can be maintained in the event of a grid connections failure and to provide module power during towing operations. A DC charger system to keep the batteries topped up while the device is connected is also needed. These requirements do not scale as the PTO increased in size and can be considered a fixed cost per PTO system, regardless of the number of generators included. The P2 DC supply, charger and battery system (including enclosure and mounting components) cost £10,000. Similar costs would be expected for any PTOs in of the power outputs being considered.

4.3.7 ELECTRICAL SYSTEM SUMMARY COSTS

The cost metrics derived are based on the P2 PTO as design and operated. An 80kW and a 125kW generator was installed in the secondary PTO system in each module for the P2 machine. The table below summarise the cost metrics derived for the electrical components of a PTO system and enables approximate electrical costs per generator to be calculated. The column on the far right indicates the total cost for the secondary PTO system in each module for the P2. Additionally, estimated costs for PTO electrical components for larger generators, rated at 185kW and 250kW, are also provided. These ratings are used in section 7 in order to provide total indicative costs for full secondary PTO systems of different electrical ratings from 205kW to 1MW.

Component	Rating (kW)				P2 PTO
	80	125	185	250	80 + 125
Generators	£4,720	£7,500	£11,655	£16,000	£12,220
LV Switchgear	£4,500	£4,500	£5,000	£5,000	£9,000
Instrumentation	£600	£600	£600	£600	£1,200
SCADA Control	£2,500	£2,500	£2,500	£2,500	£5,000
Wiring	£500	£500	£500	£500	£1,000
DC Supply & Batteries					£10,000
Total	**£12,820**	**£15,600**	**£20,255**	**£24,600**	**£38,625**
Cost/kW	**£160**	**£125**	**£109**	**£98**	**£188**

Table 20: Estimated secondary PTO electrical costs based on P2 experience

The graph below illustrates how the cost of a service (generator, switchgear and control requirements) varies as the individual generator rating increases. The reduced cost as rating increases occurs because the system component costs additional to the generators remain almost constant as the generator rating increases.

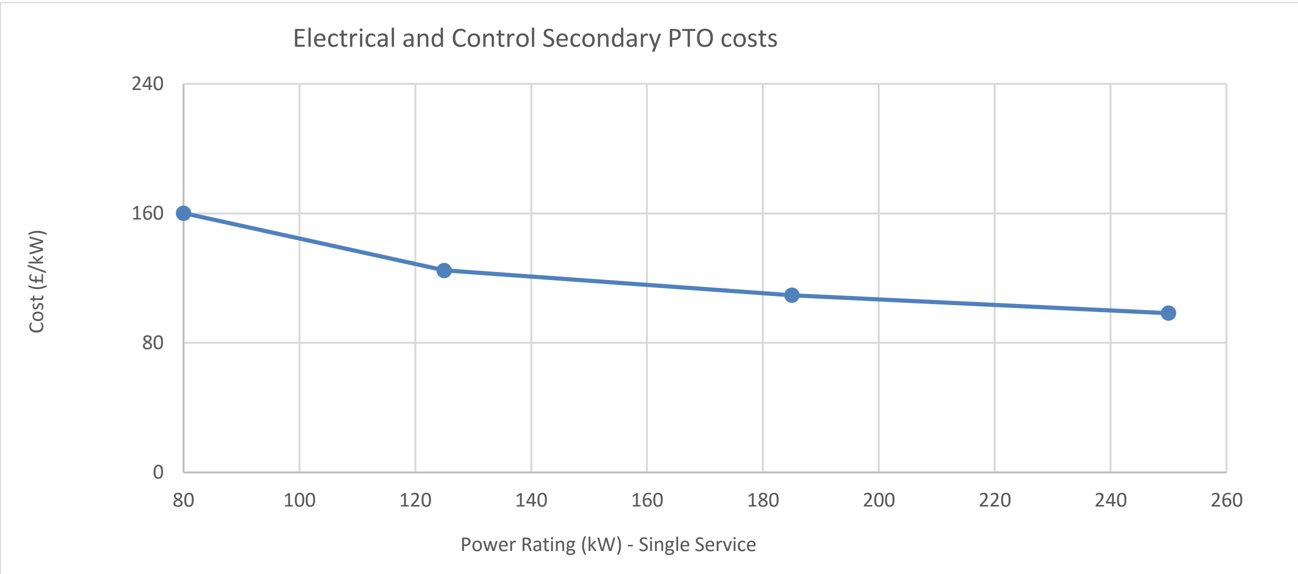

Figure 20: Cost per kW descrease per genertor in electrical costs as generator rating increases

5. ELECTRICAL COMPONENTS EXTERNAL TO THE PTO SYSTEM

5.1 LOW TO MEDIUM VOLTAGE ELECTRICAL SYSTEM

The primary and secondary PTO systems incorporate all electrical and control systems components to the point of connection on the 690Vac power and the 415Vac auxiliary busbars that run along the length of the Pelamis. In the Pelamis example, between the LV connection point on the secondary PTO and the MV connection at the wet-mate connector, the voltage is stepped up in a separate power and auxiliary transformer to 6.6kV the voltage level applied for transmission back to shore. Additionally, there is also MV switchgear between the wet-mate and power transformer to provide isolation and protection. Given this equipment is not considered to be part of the secondary or primary PTO system it is beyond the scope of this report. The type of system and equipment installed between the defined LV and MV connection points is likely to be specific to the type of WEC technology, wet-mate/machine connection system to the subsea grid and protection/isolation requirements for each device to the grid. However, as an example cost, the P2 transformer and HV switchgear cost in the region of £25k.

5.2 GRID COMPLIANCE

The electrical output of the secondary PTO is smoothed by regulating the power output from energy stored in the high pressure hydraulic system. This smoothed output, in combination with localised power factor correction on each secondary PTO system, and by using a timed interlock system to prevent simultaneous starting of generators, ensured that the single P2 installation at EMEC complied with the local grid requirements. Additional power conditioning equipment was therefore not required at the shore substation. It is known that as the installed capacity increases the grid compliance requirements become more onerous. Feasibility studies into the grid compliance requirements for a farm or array of P2 WECs indicate that additional power conditioning equipment may be required and that this could be provided by use of a STATCOM at the shore substation. A report produced by Xero energy in 2010 reviewing the requirements for a 10MW farm installation in Shetland gave an indicative cost of £750K for STATCOM.

5.3 FLEXIBLE CABLE TRANSIT

Standard COTS cable is used along the length of the Pelamis for the power and auxiliary busbars, where the cable spans a hinged joint on the Pelamis a flexible cable system was implemented. This flexible cable is situated in the splash zone, due the specific dynamic and environmental requirements for this cable a bespoke cable was manufactured by Lapp Muller. It is not possible to define a simple cost metric for assessing the cost of the cable transit, given the bespoke nature of the cable according to the specific power, auxiliary supply and communication requirements. However, to provide some indicative costs the table below provides specific costings for cable types used in the Pelamis.

Cable Construction (Copper Core)	Cost (£/Metre, MOQ 100M)
3 off - 185mm², 1 off - 95mm², 10 off - 6mm²	230
6 off - 95mm², 1 off - 70mm², 6 off - 10mm²	230

Table 21: Cable transit cable cost metrics

The total cost for the cable transit across a representative P2 cable transit was therefore around £2000. The bracketry and cable support systems associated with the cable transit system cost £1000 per transit.

6. METRICS AND SCALABILITY WITH RESPECT TO PRIMARY TRANSMISSION

The relationship between power ratings and different WEC dimensions depends heavily on the nature of the WEC. The choice of scale for a WEC should be made to achieve optimal economics overall. This is a complex function of the hydrodynamics and the wave resource, but crucially also a highly complex function of the detailed design of the structures and systems.

Any choice on WEC scale seeks to balance benefits in absorption against changes in capital and through-life costs. For example, a larger WEC may benefit from greater average absorption without proportionate increases in fixed costs for moorings or site construction. Fewer and larger WECS may also offer more efficient O&M but this must be balanced against robust overall availability aggregated over multiple machines. More subtly, different elements of the structure and systems scale in different ways with different cost implications, and different design parameters require different compromises.

For example, in the Pelamis structure, increased bending moments associated with larger main tube diameter (increasing in proportion) is accompanied by an increase in the section modulus (the capacity to carry bending moment, increasing with third power) such that the wall thickness does not need to increase in proportion, resulting in an apparent fundamental structural cost advantage for larger machines. However, in detailed design it is found that larger panels require additional stiffening and/or additional wall thickness to protect against local buckling, mitigating the advantage. Similarly larger bending moments require additional load capacity on attachments of point loads and their bearing systems, requiring detailed design and analysis to bottom out. These aspects, which dominate the high-level scaling decisions in WEC development, are beyond the scope of this work package, which focuses solely on the issues associated with scaling the power take-off systems.

6.1 INTERACTION OF PRIMARY TRANSMISSION WITH COST OF STRUCTURES

The main structural components not considered in the PTO system treatment above were the main tube fabrications (including module and end cap structures) and the main joint bearings. While these are not directly part of the primary transmission, they are treated here in brief to provide a context of the total cost of a Pelamis WEC, as these items were the largest contributors. During the design process, cost optimisation was focussed on these prime mover components and integration of the primary transmission elements into them in order to achieve the best solution for the complete WEC system. While it is likely that the cost of the primary transmission elements could be lower if optimised in isolation, this would likely result in a more expensive total machine cost as there would be associated increases in the cost of connecting components.

It is therefore very important that all primary systems relating WEC response and loads to structural and PTO components are designed and specified to a suitable level of detail in conjunction, by a highly integrated design team with full oversight – they cannot be specified for design in isolation above the individual component level.

For example, isolated optimisation of the hydraulic cylinders to achieve a desired motion and load specification would likely result in a shorter stroke, higher force cylinder brought inboard to maintain the joint angle range but still meeting the required joint moments (approximately 5.5MNm per cylinder) however this would have a double effect on the cost of the associated structural mounting points.

Firstly, the shorter stroke would require the cylinder to operate inboard of the main tube body, which would necessitate additional structural steel to support the offset load from the tube hull.

Secondly, the fatigue of the main fabrications is related to force (and subsequently stress) by a cubic law e.g. by doubling the stress range, the fatigue life is reduced by (2^3=) 8 times. Increasing the localised force generated by the cylinder requires additional structural steel in order to combat the localised increase in force/stress and maintain the required fatigue life. This local load path requirement also applies to the bearings connecting the cylinder to the structure, a larger force cylinder would require larger rod-end and rear bearings, which would add more cost than would be saved on the cylinder itself.

6.2 P2 STRUCTURAL FABRICATIONS

The main structural fabrications can be split into two categories: basic and complex. The cost of these 2 types can be estimated at different rates, which is affected by the level of man-hours required to fabricate the individual steel sections. A brief description can be seen below:

- Basic – Large, simple shaped structures (e.g. cylinders, flat plates) with minimal additional connected pieces and minimal alignment tolerances. Significant levels of automation possible during production (e.g. sub-arc welding), minimal fit-up requirements and no positional manual welding
- Complex – Large, intricate structures containing many individual plate pieces, potentially with tight alignment tolerances for the inclusion of machined parts. Significant set-up time (manual) required with reduced / no allowance for automated production methods. Potential requirement for positional manual welding.

With application to the Pelamis P2 machines, the main tube bodies were considered as basic fabrications and the module, end cap and yoke fabrications as complex fabrications.

Fabrications are estimated based on an assumed £ rate/tonne based on the type of fabrication. Typically, a basic fabrication cost will be around £2,000/tonne to £2,500/tonne with a complex fabrication around £3,500/tonne. Steel raw material is not included in these values, and is often higher for complex fabrications due to the inclusion of thicker (40mm+) steel plates for load bearing points. At the time of the production of the P2 machines this was around £600/tonne.

Fabrication	Mass (Te)	Quantity	Cost Ea.	Cost Total	£/Te
Module	45	4	£184,500	£738,000	£4,100
End Cap	25	4	£102,500	£410,000	£4,100
Main Tube	54	4	£140,400	£562,000	£2,600
Nose Tube	88	1	£294,800	£295,000	£3350
Yoke	16	1	£65,600	£65,600	£4,100
Total				**£2,070,000**	

Table 22 : Fabrication rates inclusive of material costs.

Note the nose tube contains both complex and basic fabrications, hence its fabrication rate is taken as the mean value of the two different rate options. Because the fabrication contract was ‘lump sum’, costs are estimates based on the approximate fabrication mass and an assumed fabrication rate. These rates will also assume a level of scrap production during the process (typically around 15% for large fabrications).

6.3 P2 MAIN BEARINGS

The main joint bearing system for the Pelamis P2 was a significant cost centre for the machine. This unit was a large 2 degree-of-freedom universal joint which enable ~30 degrees of articulation. It weighed approximately 15 tonnes and cost approximately £90,400 excluding the tooling required to assemble and connect the unit to the end structures. A P2 Pelamis machine required 4 units (1 per joint), totalling approximately £361,600. This cost also does not include the passive spring system and associated pneumatic inflation systems for the bellow seal units.

The main bearing assembly included 4 off radial maintenance free spherical plain bearings, and 4 off axial maintenance free spherical bearings. The bearings had the following load ratings and metrics:

Bearing	Dynamic load rating	Static load rating	Mass	£/kg
GE320 Radial	12.92MN	21.54MN	76kg	£40
GE260AQ Axial	10.8MN	18MN	71.3kg	£31
Main bearing assembly	--	--	15,000kg	~£6

Table 23: Main Bearing load ratings and metrics

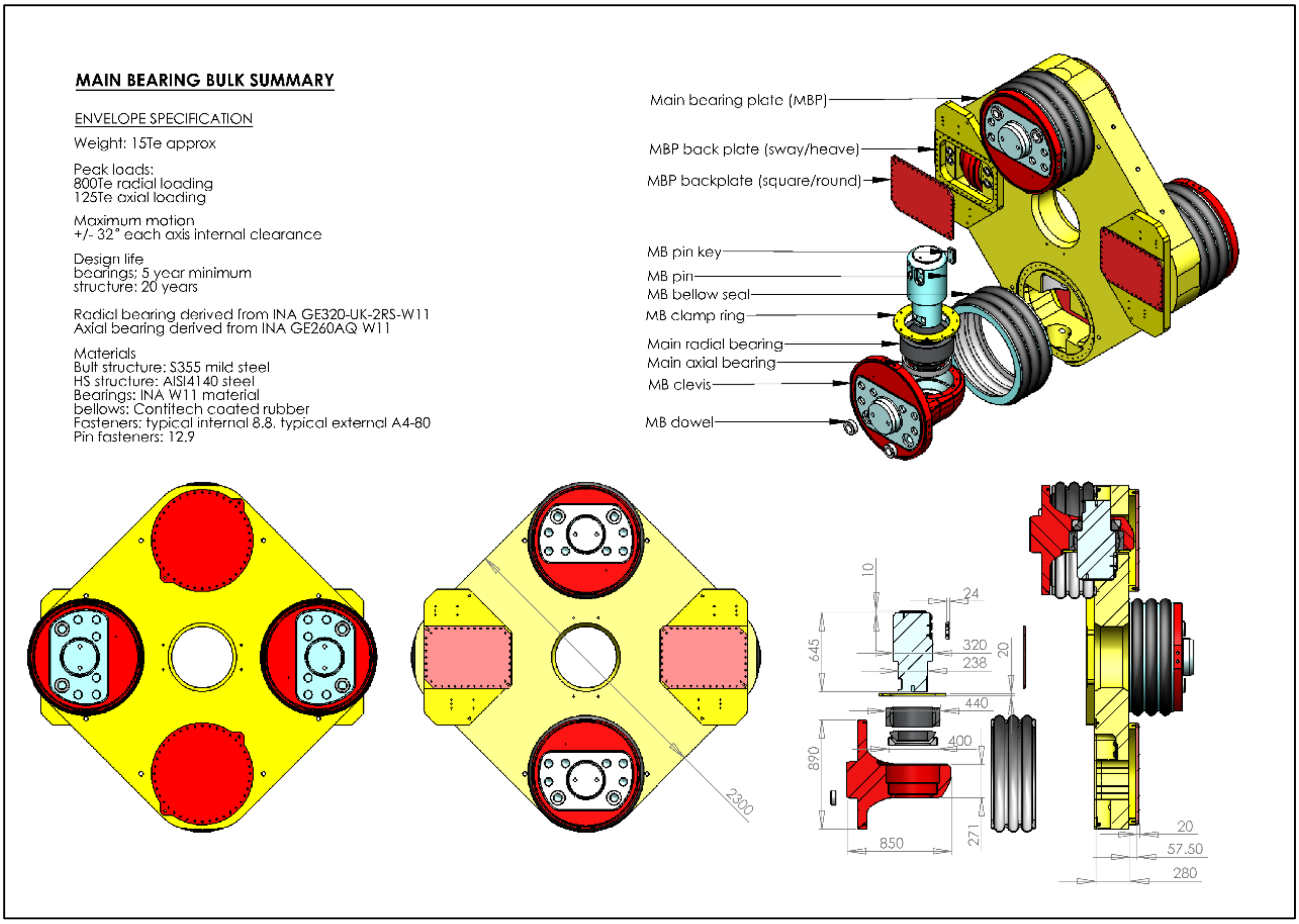

Figure 21 : Main bearing general assembly

The design of the main bearing was optimised to meet the machine load and motion regime produced by the P2 machine. This included reaction forces generated by the primary PTO system, and environmental loads produced by the hydrostatic and hydrodynamic loads on the main structural elements.

For a 205kW PTO unit in a Pelamis P2 machine, the main fabricated items (1x module, 1x end cap, 1x main tube) and the main joint bearing assembly required to provide the prime mover for such a PTO unit cost approximately £517,800. This value is greater than the cost of the complete PTO system, and indicates the importance of consideration of the complete machine when considering the cost of any given system.

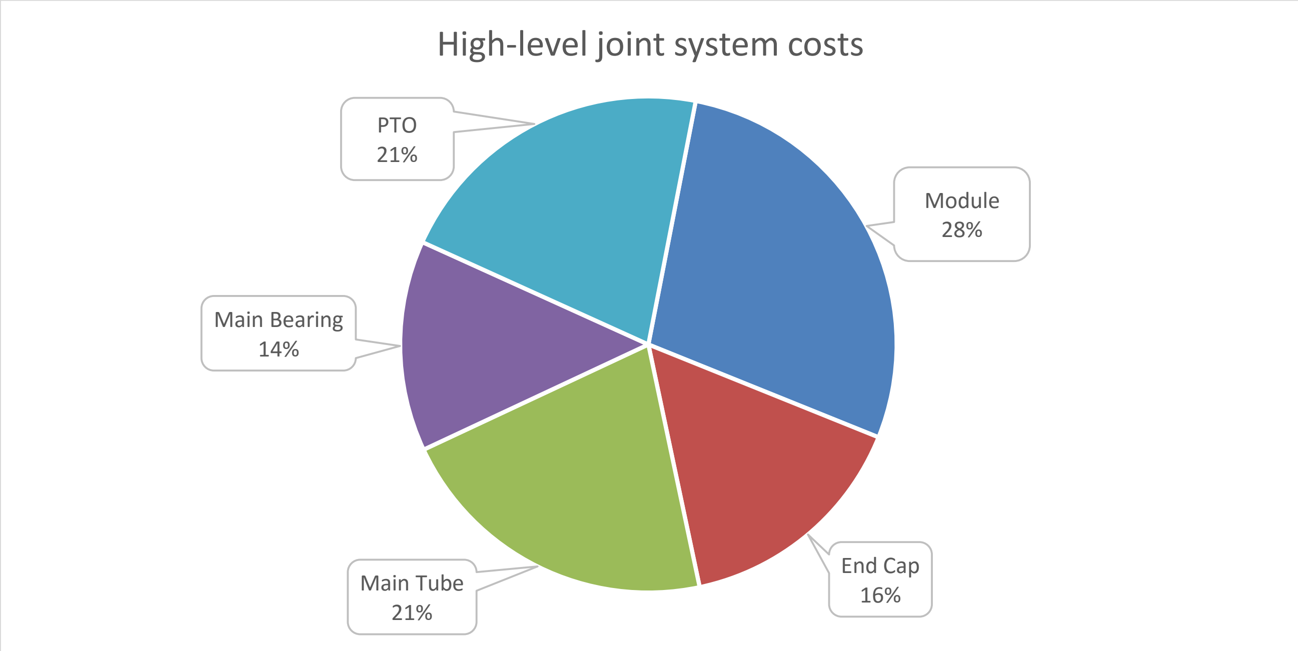

Figure 22 : Cost distribution of P2 articulated joint and PTO system

6.4 EXAMPLE OF SCALE UP FROM P2 TO P3

The as built Pelamis P2 is used as the benchmark for PTO costs and metrics discussed in this report. Wherever possible scaling metrics are generalised, although for the reasons discussed above this is only reliable for the secondary transmission and energy storage systems due to the complex interactions with loads, structure, and motion ranges on the primary systems. The development programme for the larger P3 machine arrived at a reference design which can also referenced directly to provide a benchmark for cost variation with changes in scale and power.

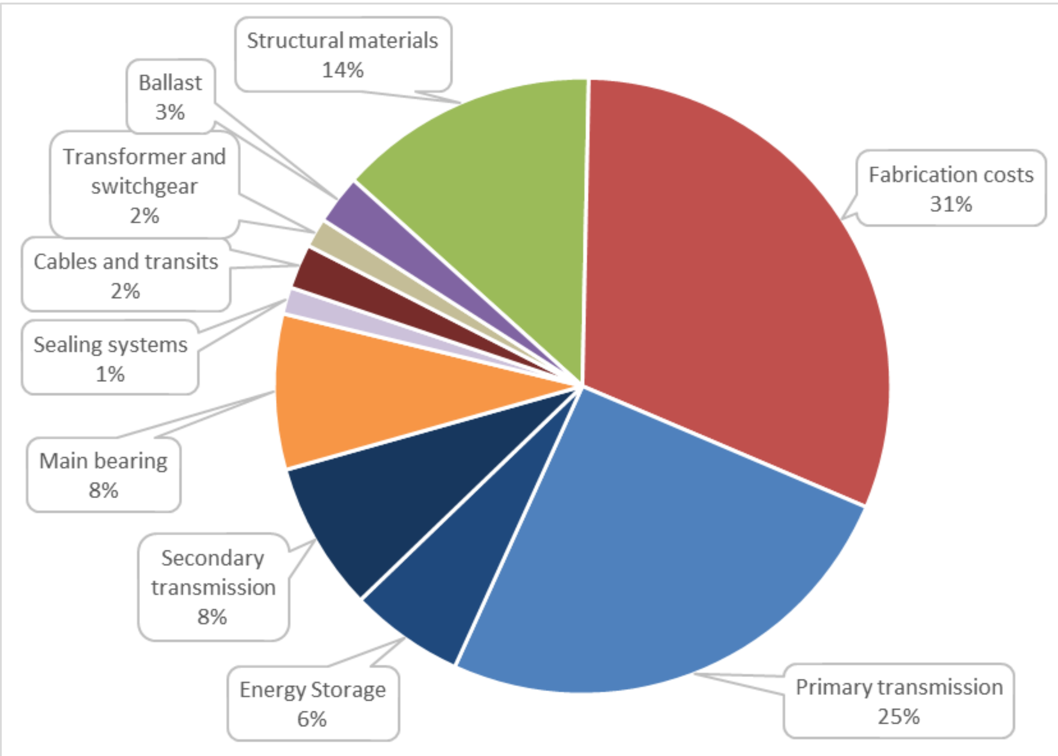

Figure 23 : Breakdown of P2 machine parts costs (£4.2m total)

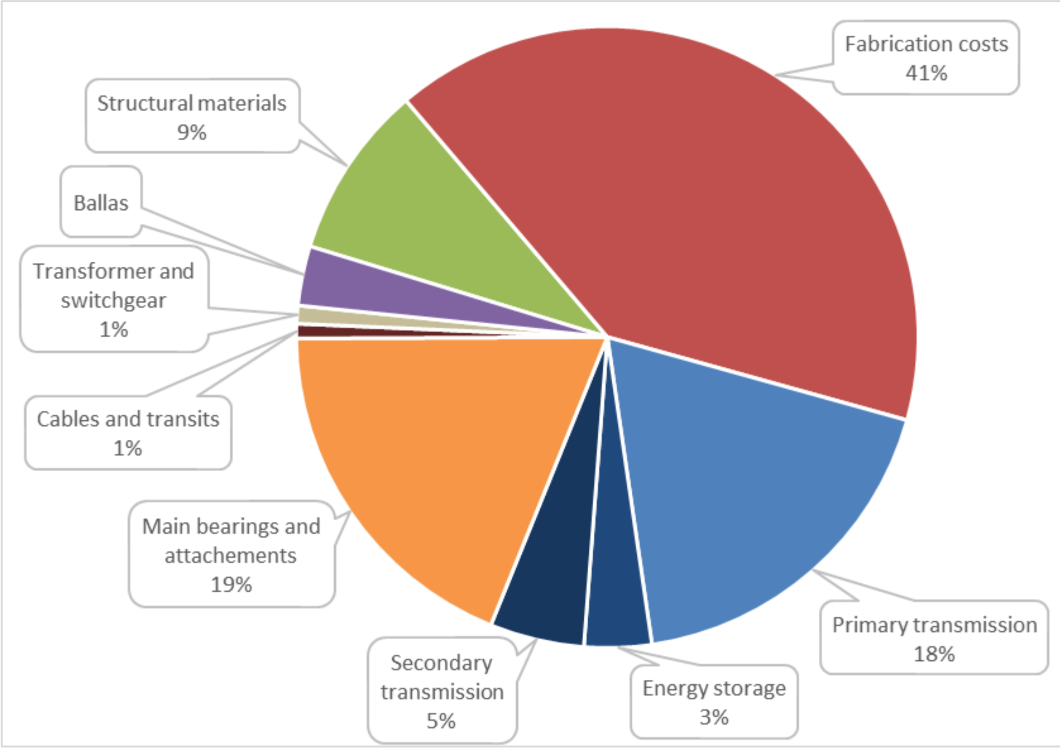

Figure 24 : Breakdown of P3 machine part costs (£8.2m total)

The projected proportion of overall costs attributable to PTO remained similar for the P3 design from the P2, reducing slightly due to better utilisation of some fixed costs and elements. This is despite the architecture of the machine changing substantially. This is highlighted further in the table and figures below:

	P2	**P3 reference design**
Machine architecture	4 x 2 DOF joints.	6 x 1 DOF joints.
No of modular PTOs	4	3
PTO Electrical rating / continuous	205kW / 140kW	685 / 465kW
PTO costs		
Primary transmission	£276,000 (65%)	£496,000 (68%)
Energy storage	£66,000 (15%)	£98,000 (13%)
Secondary transmission	£84,000 (20%)	£138,000 (19%)
Total for joint	**£426,000**	**£732,000**

Table 24 : High level cost breakdown of P2 and P3 PTOs

While the architecture of the joints evolved following extensive engineering review, the cost relationship between the two designs was broadly consistent. The proportion of the cost attributed to the primary transmission had increased from 65% to 68% whilst the relationship between the energy storage and the secondary transmission remained similar.

7. INTEGRATED COSTING OF SECONDARY TRANSMISSIONS & ENERGY STORAGE

To provide an overall metric of cost against electrical output rating for the secondary transmission and energy storage, explicit examples are given below. This takes into account breakpoints in the design of subsystems and detailed individual subsystem and component costs. The integrated system is based around different sizes and combinations of motor-generator sets, with other functions scaled accordingly either through change of size. The costs are explicitly derived for combinations of individual sets of 80kW, 125kW, 185kW, and 250kW.

With larger total ratings achieved in combination for the whole secondary transmission. This combination of multiple generation units is a key design feature for increased part load efficiency and for greater fault tolerance.

An overview of the results obtained can be seen in Figure 25 below. This analysis indicates that the biggest cost savings can be achieved in the move from the P2 (205kW electrical rating) to the 435kW (electrical rating) system. The 435kW system is based on the P3 design that was well underway at the point of PWP administration. Some design optimisation had taken place between the P2 system and the proposed P3 design (including some decrease in the level of accumulation required, a significant cost driver). Much of the reduction however, is due to the fixed costs are not being repeated at the PTO system becomes larger or the per generator costs have relatively less impact on the price. Additionally, the increased costs to account for the larger flows in the higher rated systems reduce the cost savings possible.

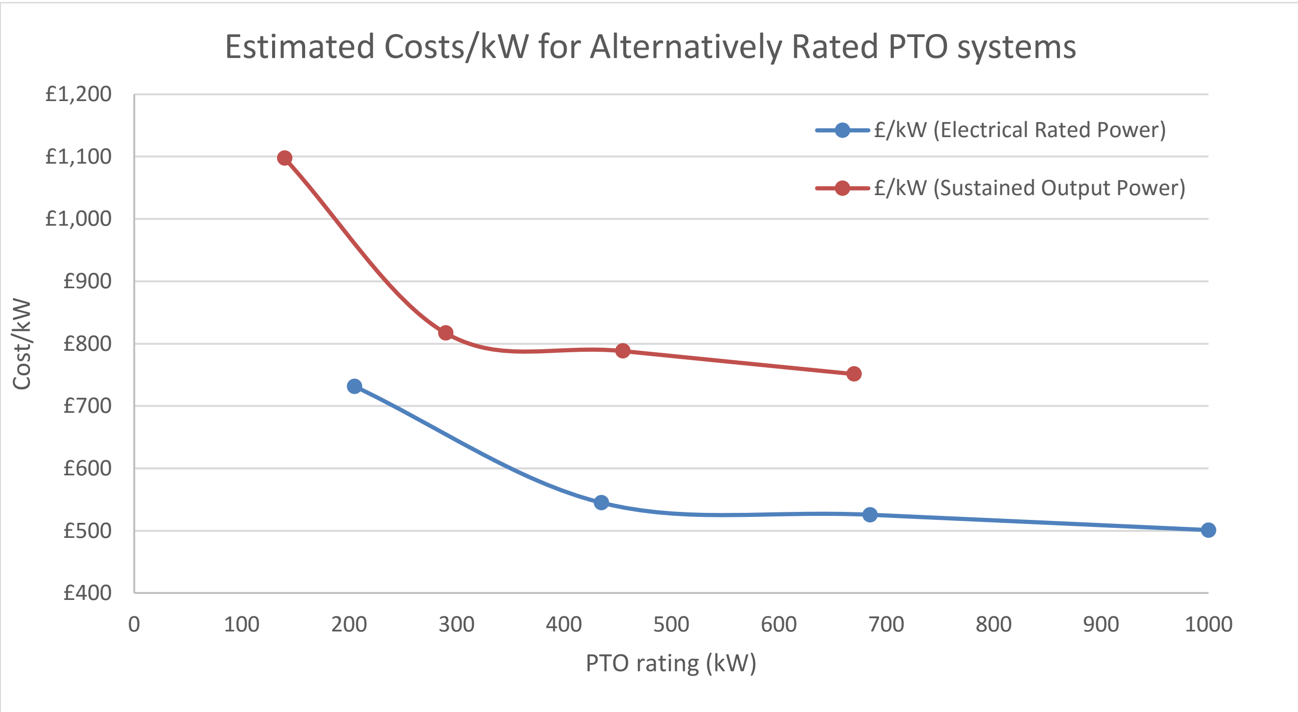

Figure 25: Calculated cost metrics for integrated PTO systems of different rated output powers (both costs/kW of sustained output power and cost/kW of total electrical rating are shown)

7.1 205KW ELECTRICAL RATING (P2) – 125KW + 80KW GENERATORS

System Rating	**205**	**kW (electrical rating)**			
Energy Storage					
System Component		**Description**	**Cost / Cost Metric**		**Total**
Accumulators (inc. structure & ancillary components	960	L (6 x 160L accumulators)	£26.00	£/L	£24,960
Accumulator Back-up Bottles	1050	L (14 x 75L BUBs)	£6.50	£/L	£6,825
Reservoirs (inc. structure, BUBs & ancillary components	2400	L (2 x 1200L reservoirs	£11.90	£/L	£28,560
Hydraulic oil	2000	L	£1.75	£/L	£3,500
Nitrogen Gas	1	P2 Unit Cost per PTO	£2,000	£	£2,000
Energy Storage Sub Total					**£65,845**
Secondary PTO Components					
System Component		**Description**	**Cost / Cost Metric**		**Total**
Electrical & Control					
Generators	205	kW (1 x 80kW+1 x 125kW)	£60	£/kW	£12,300
LV Switchgear	2	P2 Unit cost for 80/125kW gens	£4,500	£/gen	£9,000
Hydraulic Sensors	2	P2 Unit Cost per generator	£600	£/gen	£1,200
Control System	2	P2 Unit Cost per generator	£2,500	£/gen	£5,000
Wiring & Cable management	2	P2 Unit Cost per generator	£1,000	£/gen	£2,000
DC Charger System & Batteries	1	P2 Unit Cost per PTO	£11,000	£/PTO	£11,000
Hydraulic					
Motors	220	cc (1x60cc/rev + 1x160cc/rev)	£30	£/cc	£6,600
Manifolds	1	P2 Unit Cost	£6,100	£	£6,100
Filtration Systems	2	P2 Unit Cost per gen + £900	£650	£	£2,200
Heat Management	300	kW	£24	£/kW	£7,050
MG Set Structural	1	P2 Unit Cost per PTO	£5,500	£	£5,500
Ancillary Hydraulic	1	P2 Unit Cost per PTO	£10,000	£	£10,000
Ancillary Hydraulic (fixed costs)	1	P2 Unit Cost per PTO	£6,000	£	£6,000
Secondary Transmission Sub Total					**£83,950**
Grand Total *(nearest £1000)*					**£150,000**
Cost/kW (electrical rating)					**£731**
Cost/kW (Max sustained power output)					**£1,096**

N.B. the costs above have been calculated according to the metrics derived throughout this document. However, the resultant total costs are within 5% of the actual costs incurred during the build of the P2 PTO.

7.2 435KW (2 X 125KW + 185KW)

System Rating	**435**	**kW**			
Energy Storage					
System Component		**Description**	**Cost / Cost Metric**		**Total**
Accumulators (inc. structure & ancillary components	1600	L (10 x 160L accumulators) (1)	£26.00	£/L	£41,600
Accumulator Back-up Bottles	2100	L (28x 75L BUBs)	£6.50	£/L	£13,650
Reservoirs (inc. structure, BUBs & ancillary components	3000	L (2 x 1500L reservoirs	£11.90	£/L	£35,700
Hydraulic oil	2500	L	£1.75	£/L	£4,375
Nitrogen Gas	1.5	P2 Unit Cost per PTO	£2,000	£	£3,000
Energy Storage Sub Total					**£98,325**
Secondary PTO Components					
System Component		**Description**	**Cost / Cost Metric**		**Total**
Electrical & Control					
Generators	435	kW (2 x 125kW + 1 x 185kW)	£60	£/kW	£26,100
LV Switchgear 1	2	P2 Unit costs for 80/125kW gens	£4,500	£/gen	£9,000
LV Switchgear 2	1	P2 Unit costs for 185/250kW gens	£5,000	£/gen	£5,000
Hydraulic Sensors	3	P2 Unit Cost per generator	£600	£/gen	£1,800
Control System	3	P2 Unit Cost per generator	£2,500	£/gen	£7,500
Wiring & Cable management	3	P2 Unit Cost per generator	£1,000	£/gen	£3,000
DC Charger System & Batteries	1	P2 Unit Cost per PTO	£11,000	£/PTO	£11,000
Hydraulic					
Motors	570	cc (2x160cc/rev + 1x250cc/rev)	£30	£/cc	£17,100
Manifolds	2	P2 Unit Cost per PTO (2)	£6,100	£	£12,200
Filtration Systems	3	P2 Unit Cost per gen + £900	£650	£	£2,850
Heat Management	360	kW (3)	£24	£/kW	£8,460
MG Set Structural	1.5	P2 Unit Cost per PTO	£5,500	£	£8,250
Ancillary Hydraulic	2	P2 Unit Cost per PTO	£10,000	£	£20,000
Ancillary Hydraulic (fixed costs)	1	P2 Unit Cost per PTO	£6,000	£	£6,000
Secondary Transmission Sub Total					**£138,260**
Grand Total *(nearest £1000)*					**£237,000**
Cost/kW (electrical rating)					**£544**
Cost/kW (Max sustained power output)					**£816**

(1) Level of accumulation per kW has been reduced compared to P2. This is in line with the design work completed for P3 although levels of accumulation required are dependent on resource and power absorption characteristics or the WEC and are a subject in which further work is required.
(2) Only one extra generator is used in this system but additional flow and increased efficiency requirements will increase the size (The additional 33% increase in cost brings the manifold cost for this system in line with quotes received for a P3 manifold £11,500)
(3) Heat exchanger requirements reduced compared to P2 based on experience gained. Now more in line with sustained max power output.

7.3 685KW (1 X 250KW, 2 X 125KW, 1 X 185KW)

System Rating	**685**	**kW**			
Energy Storage					
System Component		**Description**	**Cost / Cost Metric**		**Total**
Accumulators (inc. structure & ancillary components	2240	L (14 x 160L accumulators)	£26.00	£/L	£58,240
Accumulator Back-up Bottles	3300	L (44 x 75L BUBs)	£6.50	£/L	£21,450
Reservoirs (inc. structure, BUBs & ancillary components	5600	L (4 x 1400L reservoirs	£11.90	£/L	£66,640
Hydraulic oil	5000	L	£1.75	£/L	£8,750
Nitrogen Gas	2.5	P2 Unit Cost per PTO	£2,000	£	£5,000
Energy Storage Sub Total					**£160,080**
Secondary PTO Components					
System Component		**Description**	**Cost / Cost Metric**		**Total**
Electrical & Control					
Generators	685	kW (2x125kW + 1x185kW, 1x250kW)	£60	£/kW	£41,100
LV Switchgear	4	P2 Unit cost for 185/250kW gens	£5,000	£/gen	£20,000
Hydraulic Sensors	4	P2 Unit Cost per generator	£600	£/gen	£2,400
Control System	4	P2 Unit Cost per generator	£2,500	£/gen	£10,000
Wiring & Cable management	4	P2 Unit Cost per generator	£1,000	£/gen	£4,000
DC Charger System & Batteries	1	P2 Unit Cost per PTO	£11,000	£/PTO	£11,000
Hydraulic					
Motors	925	cc (2x160cc/rev, 1 x 250cc/rev, 1x355cc/rev)	£30	£/cc	£27,750
Manifolds	3	P2 Unit Cost (1)	£6,100	£	££18,300
Filtration Systems	5	P2 Unit Cost per gen + £900 (2)	£650	£	£4,150
Heat Management	500	kW	£24	£/kW	£11,750
MG Set Structural	2.5	P2 Unit Cost per PTO (3)	£5,500	£	£13,750
Ancillary Hydraulic	3	P2 Unit Cost per PTO	£10,000	£	£30,000
Ancillary Hydraulic (fixed costs)	1	P2 Unit Cost per PTO	£6,000	£	£6,000
Secondary Transmission Sub Total					**£200,200**
Grand Total *(nearest £1000)*					**£360,000**
Cost/kW (electrical rating)					**£526**
Cost/kW (Max sustained power output)					**£789**

(1) 1 extra motor compared with 435kW system (includes 50% increase in cost for manifolds compared to P2 for increased flow and efficiency requirements)
(2) Assume filtration costs for larger motor circuits will be 1.5x that of the P2 system per generator
(3) 2* Number of generators compared to 2 in P2, plus addition ~25% cost increase to account for increased size of components

7.4 1MW (4 X 250KW)

System Rating	**1 MW**				
Energy Storage					
System Component	**Description**		**Cost / Cost Metric**		**Total**
Accumulators (inc. structure & ancillary components	3200	L (20 x 160L accumulators)	£26.00	£/L	£83,200
Accumulator Back-up Bottles	4950	L (66 x 75L BUBs)	£6.50	£/L	£32,175
Reservoirs (inc. structure, BUBs & ancillary components	8400	L (6 x 1400L reservoirs	£11.90	£/L	£99,960
Hydraulic oil	7000	L	£1.75	£/L	£12,250
Nitrogen Gas	3.5	P2 Unit Cost per PTO	£2,000	£	£7,000
Energy Storage Sub Total					**£234,585**
Secondary PTO Components					
System Component	**Description**		**Cost / Cost Metric**		**Total**
Electrical & Control					
Generators	1000	kW (4 x 250kW)	£60	£/kW	£60,000
LV Switchgear	4	P2 Unit costs for 185/250kW gens	£5,000	£/gen	£20,000
Hydraulic Sensors	4	P2 Unit Cost per generator	£600	£/gen	£2,400
Control System	4	P2 Unit Cost per generator	£2,500	£/gen	£10,000
Wiring & Cable management	4	P2 Unit Cost per generator	£1,000	£/gen	£4,000
DC Charger System & Batteries	1	P2 Unit Cost per PTO	£11,000	£/PTO	£11,000
Hydraulic					
Motors	1420	cc (4x355cc/rev)	£30	£/cc	£42,600
Manifolds	4	P2 Unit Cost (1)	£6,100	£	£24,400
Filtration Systems	6	P2 Unit Cost per gen + £900 (2)	£650	£	£4,800
Heat Management	700	kW	£24	£/kW	£16,450
MG Set Structural	3	P2 Unit Cost (3)	£5,500	£	£16,500
Ancillary Hydraulic	4	P2 Unit Cost per PTO	£10,000	£	£40,000
Ancillary Hydraulic	1	P2 Unit Cost per PTO	£6,000	£	£6,000
Secondary Transmission Sub Total					**£266,150**
Grand Total *(nearest £1000)*					**£501,000**
Cost/kW (electrical rating)					**£501**
Cost/kW (Max sustained power output)					**£751**

(1) Assume equivalent cost per generator when compared to P2 is doubled to account for doubled flow for 250cc/rev motors (plus efficiency improvement modifications)
(2) Assume filtration costs will be 1.5x that of the P2 system per generator
(3) 1 extra generator compared to 685kW system

8. P2 PTO COST BREAKDOWN REPRESENTATION