Hybrid Digital Displacement® hydraulic PTO for wave energy

WES Power Take Off
Stage 2 Project
Public Report

Artemis Intelligent Power

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

Artemis Intelligent Power Ltd and Quoceant Ltd have teamed up to deliver the 'Quantor' Power Take Off system, a major advance in hydraulic power take off systems for renewable energy applications.

This project successfully demonstrated the necessary control and machine functionality to integrate Artemis Digital Displacement Pump-motor (DDPM) technology into the state of the art ex-Pelamis Power Take-off (PTO) systems to produce a new 'hybrid' with a combined capability greater than the sum of the parts. The highly innovative system offers high bandwidth and continuously variable control of loads with the proven and unrivalled efficiency and power handling capability of the ex-Pelamis system.

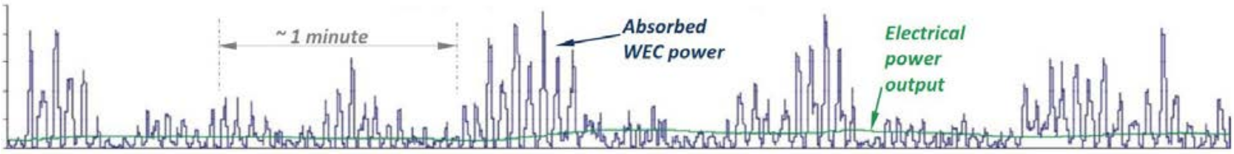
We believe that such a PTO system represents a major advance on anything currently available or proposed in the wave sector, and may also offer some compelling benefits in other renewable and marine hydraulic applications where continuously variable, four-quadrant, efficient transmission is required over rapidly varying loads and power into the MW range. The hybrid system should come close to the ultimate limits of performance for a fluid power WEC PTO system.

1.2 Description of Project Technology

1.2.1 PTO requirements

High-pressure oil-hydraulic machines are tough and relatively cheap, with high power to weight ratio. They are naturally suited to applications with high forces and high powers, even at relatively slow speeds. Apart from oscillating water columns and wave-overtopping systems, hydraulics is an inherently good match for the power take offs (PTO) systems of most wave energy converters (WEC). However, hydraulic systems can only deliver on this promise if the overall system can be made to operate at high mean efficiency and with high controllability.

In any sea-state, the instantaneous power at the 'input' side of a WEC PTO varies cyclically from zero up to peak values that are typically an order of magnitude greater than the average power. The first challenge in developing a WEC PTO is therefore to capture input energy over a large dynamic range and to export it as electrical energy at a steady average value, without undue wastage. This implies a high efficiency across a very wide range of instantaneous power absorption, something that is not possible with conventional transmissions.



Typical PTO input and output power waveforms, from Pelamis data.

Short-term energy storage is required to smooth out peaks in power and allow generating equipment to operate efficiently and cost effectively near the average output and also to enable reactive power capability which is important to maximising power capture. Given the very high rates of energy charge and discharge, hydraulic ('gas') accumulators provide the most economic and efficient energy storage solution.

The second challenge is to make the PTO input side capable of resisting wave-induced WEC motions with whatever time-varying loads enable it to maximise the hydrodynamic wave-to-WEC energy capture. This implies variable-displacement machines that can respond quickly and faithfully to control demands with high control gain applied between the measurements and the applied forces.

With larger megawatt-scale WECs, it is likely to be advantageous if the PTO drives a conventional wound-rotor synchronous generator. These provide the best support to the local electricity grid and the most benign response to network faults.

The PTO architectures and systems studied during this project bring together various hydraulic and electrical machines to form a hybrid system that we believe is best able to meet these challenging requirements.

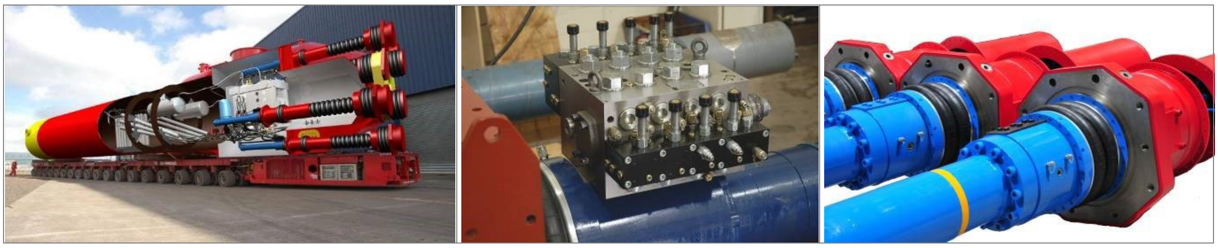
1.2.2 Drawbacks of conventional hydraulics

Continuous, high-gain force control is routinely implemented in conventional hydraulic system in one of two main ways:

1. The usual approach is to use proportional valves to control flow to or from an actuator to modulate the pressure and hence the load. This approach is fundamentally unsuited to WEC PTOs because it throttles or dissipates a large proportion off the transmitted energy.

2. Conventional hydrostatic transmissions can control force and motion more efficiently as long as the peak to average power of the system are comparable. However, fixed losses are high and at the peak to average power ratios required in wave energy they become crippling.

Therefore, if hydraulic technology is to realise its inherent potential as a WEC PTO then a different approach is required.



Pelamis switched state PTO. Left: complete system; Centre: chamber switching valve matrix mounted directly to hydraulic ram; Right: multi-chamber hydraulic rams.

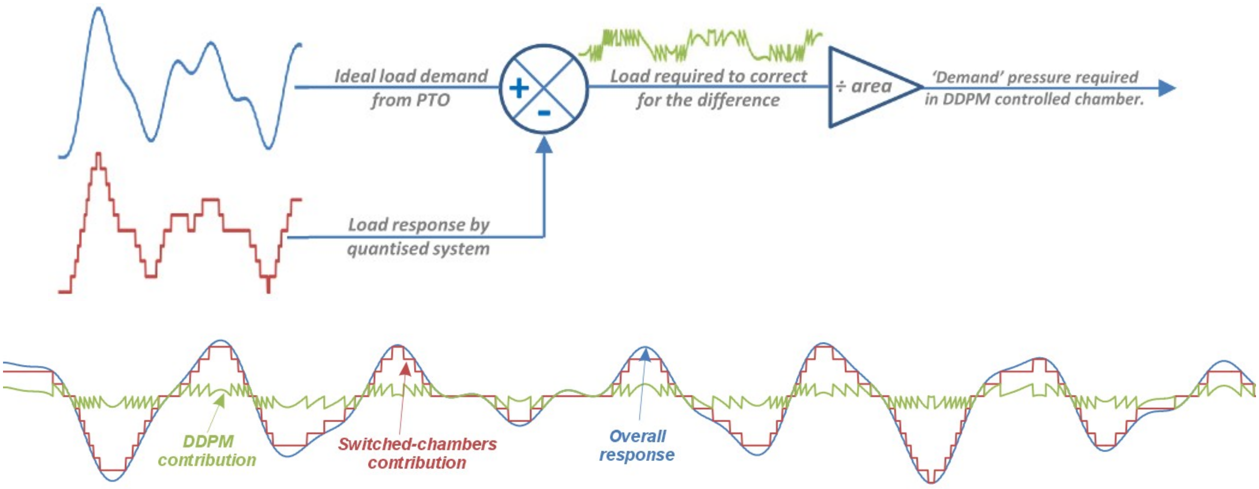
At Pelamis, Quoceant engineers successfully developed, demonstrated and refined a new approach to primary power transmission using a series of switched states to approximate a continuous load demand. A number of actuator areas (or ‘chambers’) within a hydraulic ram could be selected to be at either high pressure or low pressure. Arranging actuator areas in both directions of a WEC degree of freedom allows such a system to deliver a quantised approximation to any desired continuously varying load. The net energy absorbed from the WEC motion flows into a high-pressure accumulator from where it can be drawn off at a steady rate by conventional motor and generator sets.

The major benefit in such a primary absorption system is that the losses are limited to small volumetric and flow losses in the actuators, valves, and hoses as there is no rotating machinery and minimal restrictions in the high-power flow path. The primary transmission could achieve well over 90% efficiency across a wide range of conditions. The hydraulic motor and generator can be sized to run in their optimal design conditions most of the time, giving a high wave to wire efficiency. In operational systems at sea, the PTO efficiency from wave absorption to electrical output, averaged over a 30-minute period, was over 70% for weeks at a time and over a wide range of conditions.

The result is a system well suited to the high instantaneous powers and energy flows required whilst providing reasonable load and motion control to help optimise absorption from incoming waves. However, the quantised (stepped) nature of the output forces limits the system's ultimate energy absorption potential, particularly if only a small number of steps are available or if the inertia of the system is low. In these cases, a large amount of hysteresis is required to stabilise the system, the phase shift and memory effect of which inhibits the ability to apply optimal WEC control algorithms.

An optimum hydraulic PTO system would combine the high efficiency of the quantised system with the ability to control force with a continuous rather than a stepped profile. The Quantor system proposed by Artemis and Quoceant has exactly this combination of attributes.

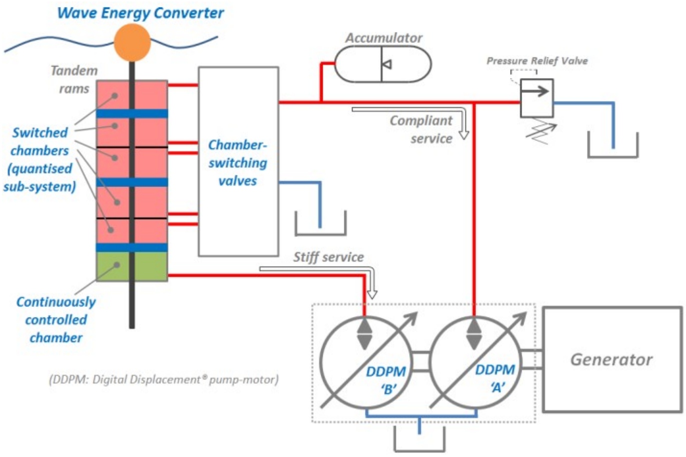
1.2.3 Quantor hybrid approach



Idealised Quantor concept. Top: the difference between the ideal continuous load-demand and the stepped profile of a quantised (switched area or switched chamber) system generates a 'correction' load signal; Bottom: The load provided by the 'DDPM' (Digital Displacement® pump-motor) combines with the quantised load to provide an overall smooth load response.

The Quantor hybrid hydraulic system marries 'quantised' or stepped force stages and continuous force control over a limited range to create a system that is capable of high bandwidth and high-gain continuous control, with a net conversion efficiency that is comparable to the quantised system on its own. This combination is expected to approach the ultimate potential of hydraulic WEC PTOs. The technical basis of such a system is shown schematically in the figures above. Most of the power is handled efficiently by the big steps in load, while some power is channelled through the continuously variable DDPM system that can operate quickly enough to compensates for the error between the ideal load demand and the stepped approximation. The controllability of the system is markedly improved, adopting the continuous load control and high bandwidth of the low power DDPM system, while still maintaining the efficiency of the quantised system for the bulk of the power transmitted.

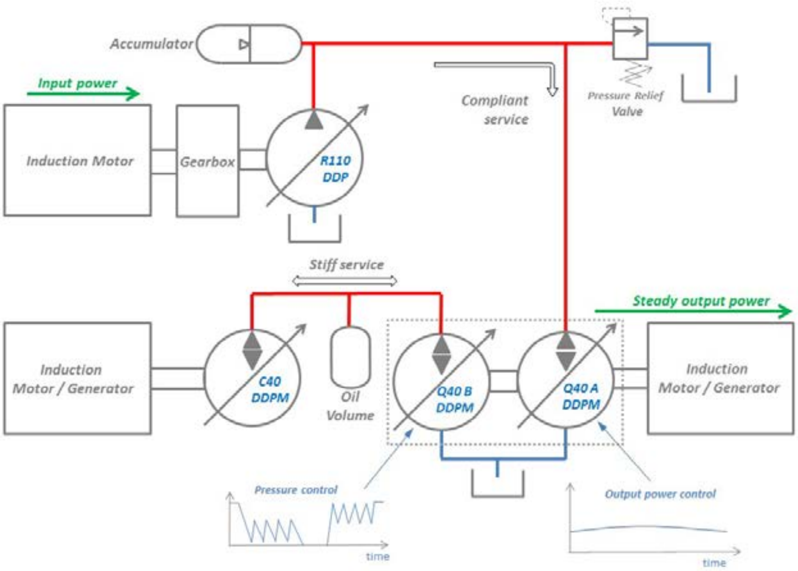
This approach offers the best combination of controllability and efficiency. However, it is technically challenging to implement and the Stage 2 PTO project summarised here was required to confirm that the required functionality and benefits were achievable in practice.



Quantor system applied to a single degree-of-freedom heaving WEC. The pressures in all but one of the (pink) chambers of a multiple chamber hydraulic ram are switched to high or low pressure to provide the basic stepped load profile from the quantised system. The load provided by the remaining (green) chamber changes sharply and in opposition at each step-change of the quantised system and then tapers to provide an overall smooth load.

1.3 Scope of Work

The major engineering challenge to implementing the Quantor system and realising a net LCoE benefit was confirming that the Artemis DDPM technology would be able to control the pressure in a PTO actuator chamber with sufficient speed and accuracy to counteract the force steps produced by the Quantised system that was previously developed and demonstrated on the Pelamis. The DDPM system has to operate with lower latency than the quantised system and with sufficient rate of change in flow rate to meet the continuous demand signal and compensate for the transient load steps.



Artemis lab test configuration to verify that the basic requirements of Quantor were technically feasible. The 'R110' ring-cam pump provides a variable flow source to represent the quantised system. The 'C40' DDPM represents the continuously controlled chamber. 'Q40' is a modified two-service Artemis DD pump-motor.

The work programme of this Stage 2 project was carefully targeted on demonstrating these core functional requirements and addressing other integration and application challenges before recommending a move to a full system test as part of a Stage 3 project. The principal tasks were to model the Quantor system in a detailed time-domain computer simulation and then to build a lab system to demonstrate and refine the main capabilities and capacities required, and carry out a range of tests to characterise the response and performance of the system.

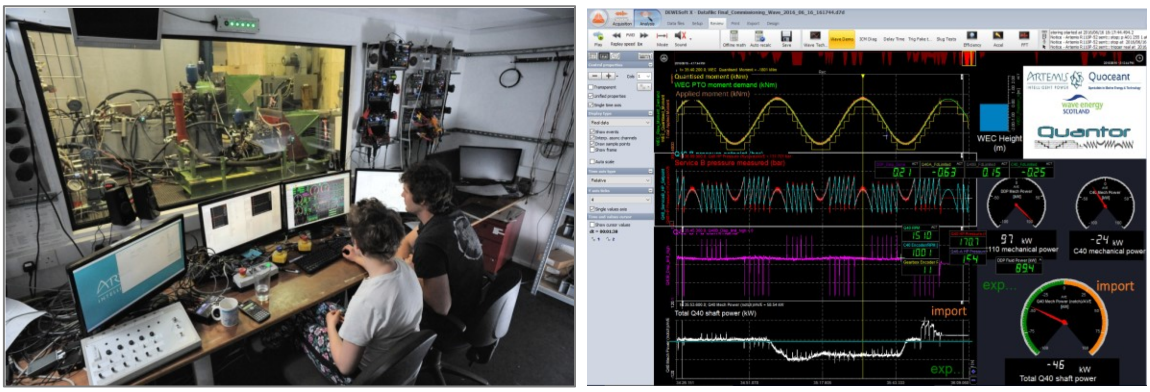
Artemis Digital Displacement® hydraulic machines. Left: 'E-dyn 96' 12-cylinder ~75kW industrial pump with controller; Centre: 'Q40' 24-cylinder pump-motor (DDPM) modified for the WES project to provide two independent 'services'; The Q40 DDPM mounted as set up for the Stage lab tests

In addition, we carried out a more thorough assessment of the range of applicability and likely route to market for an integrated Quantor system to inform the onward development and demonstration programme of a Stage 3 project. This was to make the Quantor system as relevant as possible to likely initial and future applications and included assessing responses to a technical questionnaire from a range of WEC developers and other sector applications.

Finally, we merged these two work-streams to formulate a Stage 3 project that that could hit the sweet-spot of the expected industry need and advance the lab testing of the Quantor system to a higher level of integration, so as to remove the majority of the risk before full WEC integration and at-sea demonstration as the next step.

1.4 Project Achievements

The project met its technical objectives and revealed a number of intricacies and nuances that need to be addressed in the implementation of a sea-ready system. Whilst it could have been argued that this project qualified for entry into Stage 3 from the start, the Stage 2 approach allowed key issues and risks to be addressed with the minimum of expenditure and commitment. As a result, the proposed Stage 3 programme is stronger.

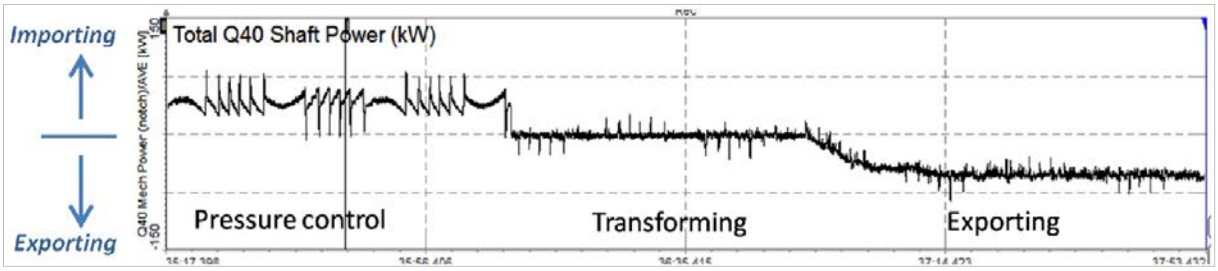


Left: control cabin of Artemis 'Wind Rig 1' during Quantor feasibility testing; Right: Dewesoft dashboard during the tests.

The market research and simulation studies that were undertaken resulted in a change to the scale and power rating of the planned Stage 3 demonstration system to better suit it to the most likely nearer-term applications. This also allows the scope of realistic laboratory testing to be extended to improve rigor and realism, significantly reducing the residual at-sea risks.

The key project achievements are perhaps best embodied in the Q40 shaft power plot below, sequentially showing from left to right:

- '*Pressure control*' - rapid control of the continuously controlled pressure by the DDPM 'B' service with the required power being drawn from its electric motor-generator.
- '*Transforming*' - pressure control, as above, but with all of the required power being supplied by the DDPM 'A' service from the accumulator. This represents the transformation of energy at one pressure (in the compliant service) to energy at another pressure (in the stiff service). No energy is drawn from or supplied to the electric motor-generator.
- '*Exporting*' – as above, but now DDPM 'A' service is also exporting power at a steady rate to the electric motor-generator.

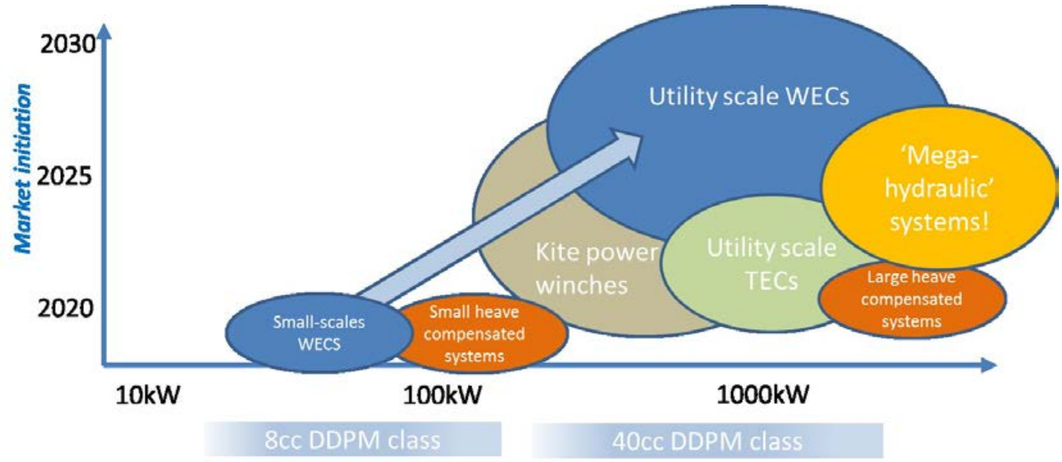


A key trace from the lab tests showing the power waveform at the shaft between the Q40 DDPM and its generator. In the first 'Pressure control' phase the generator acts as a motor to drive the 'B' service of the Q40 DDPM to provide the rapid load variation that is required from the continuously controlled chamber. In the central, 'Transforming' phase, 'B' service pumping effort is provided by Q40's 'A' service acing as a motor and drawing energy from the accumulator. In the final 'Exporting' phase, pressure control and transforming are active but power being exported from the simulated WEC.

These experiments showed that the DDPM system was capable of controlling chamber pressure to the required bandwidth in the presence of representative positive or negative fluid and power. The transforming demonstration showed that high instantaneous power exchanges could be provided with the energy storage system while delivering smooth average shaft power to the electrical generator.

Detailed simulation work was carried out on the performance impact of the Quantor system, by direct comparison with the existing state of the art system on validated simulations of the full Pelamis WEC. More basic simulations of heaving buoy WECs were also conducted to assess performance impact, including detailed loss models based on empirical data from the DDPM testing. This work led to further innovations in the Quantor system for further development in a Stage 3 project.

The market research work showed that the system would have a broad application base across a range of WEC configurations and sizes, and resulted in conception of a laboratory test rig that will enable the Quantor system to be tested and demonstrated in a highly representative and adaptable dynamic environment, de-risking onward applications. Once operational, such a rig would also be an invaluable asset for developing and proving other PTO systems, in effect a 'FloWave' or NAREC style test facility for reciprocating or rotational WEC PTOs.



The consortium's view of the route to market for PTO technology includes WEC and non-WEC applications. Most of the initial WEC interest is in the small-scale class where Artemis 8cc technology is relevant, but the ultimate utility scale market will need the development of larger PTO components.

The project demonstrated that the project partners could work together effectively and efficiently on such a complex integrated remit and project.

1.5 Applicability to WEC Device Types

The Quantor system is fully scalable and adaptable for either linear or rotational transmissions. This makes it suitable for application in a very wide range of WEC types, with the notable exception of air turbine based OWCs, over-topping systems, or other systems with a primary absorption mechanism not under direct load control. It is possible that some OWC devices could be adapted to use piston-type PTOs suitable for integration with the Quantor system.

Heaving systems, articulated line absorbers, or hinged flap systems are particularly suitable for Quantor, with the latter two allowing either linear or rotational actuation. Rotational actuators may allow for higher transmission efficiencies (a focus of Stage 3) and remove end-stops from the PTO design.

Compared with the state of the art quantised system, single degree of freedom devices and systems with relatively low inertia and high force requirements are likely to benefit more from Quantor's continuous load varying capability than those with multiple spatially separated degrees of freedom and higher inertias.

Compared with alternative technological approaches to power take-off (such as direct drive electrical systems, or air turbines) the benefits of the continuously variable, high load, high efficiency Quantor PTO are expected to be substantial.

1.6 Summary of Performance against Target Outcome Metrics

The primary objective of the Quantor system is to reduce LCoE without compromising survivability. The projected LCoE benefit from the system was carefully and extensively modelled with a number of new and specific simulation tools developed. The main components and their integration were costed. In combination we have estimated that, in a typical application, the Quantor system could reduce LCoE by around the 10% figure (compared with the quantised only system) that was targeted in the original project proposal. An extension to this analysis indicated that the quantised system itself could reduce LCoE by over 30% compared to the common approach of using a single force step 'yielding' system.

The table below summarises the LCoE calculations for Quantor and shows predicted LCoE reductions of from 0.3% to 15.3% depending on scenario.

Global assumptions	
Discount rate	8%
Nominal rated Power (kW)	125
Base capacity factor	35%
Cost range (+/-)	20%

	A		B		C		D		E	
	BASE 'SOTA' QUANTISED PTO (non-Quantor)		QUANTOR 'HIGH IMPACT' ESTIMATE		QUANTOR 'CENTRAL' ESTIMATE		QUANTOR 'LOW IMPACT' ESTIMATE		SET-POINT YIELDING SYSTEM ESTIMATE	
LCoE Calculations										
Cumulative capacity	~20MW	~1000MW	~20MW	~1000MW	~20MW	~1000MW	~20MW	~1000MW	~20MW	~1000MW
Machine installed cost	£1,000,000	£625,000	£1,072,000	£661,000	£1,090,000	£670,000	£1,108,000	£679,000	£937,500	£585,938
Balance of machine	£750,000	£468,750	£750,000	£468,750	£750,000	£468,750	£750,000	£468,750	£750,000	£468,750
Basic PTO	£250,000	£156,250	£250,000	£156,250	£250,000	£156,250	£250,000	£156,250	£187,500	£117,188
Quantor	£0	£0	£72,000	£36,000	£90,000	£45,000	£108,000	£54,000	£0	£0
Annual output	44	44	54	54	51	51	48	48	29	29
Balance of project/MW	£25,000	£12,500	£25,000	£12,500	£25,000	£12,500	£25,000	£12,500	£25,000	£12,500
commissioning allowance	£12,500	£6,250	£12,500	£6,250	£12,500	£6,250	£12,500	£6,250	£12,500	£6,250
OPEX per annum	£21,875	£8,125	£21,875	£8,125	£21,875	£8,125	£21,875	£8,125	£21,875	£8,125
Transmission efficiency	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%
Availability	93.0%	97.0%	93.0%	97.0%	93.0%	97.0%	93.0%	97.0%	93.0%	97.0%
CoE (£/MWh)	£362	£201	£309	£170	£334	£183	£361	£198	£521	£288
Impact on CoE (%)	-	-	-14.7%	-15.3%	-7.9%	-8.8%	-0.3%	-1.4%	43.9%	43.3%

Summary of estimated LCoE impact of Quantor based on 20 year life. The column 'A' figures are for the reference state-of-the-art quantised only system. The second bottom rows summarise the estimated cost of energy and the bottom row estimates the reductions in cost of energy compared with system 'A'. Columns B, C and D represent upper, mid and lower estimates for the Quantor system costs and effect on generated output. Column E represents a simple 'set-point yielding' PTO such as a flap working against a constant pressure ram. To address the effects of the scale of manufacturing, in each of the cases A to E, separate estimates are made for systems with 20 MW and with 1,000 MW of installed capacity.

Whilst costs and performance were modelled in some detail, an assumption of the analysis was that the system would not detract materially from reliability or availability of the system. While this is believed to be a reasonable assumption, detailed FMECA of the whole system in the Stage 3 project will be required to treat this key aspect more thoroughly.

The Quantor system may actually improve system survivability, as improved control response may allow implementation of better algorithms to minimise load and motion as well as maximise them. As a 'backstop', the system will revert to a quantised only system if the continuous control element fails, meaning so that survivability should not be negatively impacted by the system.

1.7 Communications and Publicity Activity

The Quantor project was promoted at the following events:

- *WES PTO Inception Workshop, 17th November 2015 in Glasgow – presentation;*
- *ICOE (International Conference on Ocean Energy) 2016, 22nd February 2016 in Edinburgh – stand;*
- *Scottish Renewables Marine Conference, 13th September 2016, Inverness – presentation, stand and leaflet;*
- *WES Annual Conference, 2nd December 2016, Edinburgh - elevator pitch and*

poster.

The Quantor project was described and promoted on the Quoceant web site blog and circulated through its social networks.

Following active press releases and promotion, the project and its potential to deliver significant new enabling technology was featured in industry news outlets including the popular and influential ReNews.

1.8 Recommendations for Further Work

Recommendations for further work were carefully considered as part of the Stage 3 plan.

Market analysis has allowed us to determine the likely WEC application requirements in the near and longer term and we also considered other renewable energy and wider applications. We believe it is important that the technology is offered to other markets in parallel to avoid the need for the wave energy market to justify and cover the respective costs of commercialisation on its own.

As a result of this research, we have determined a system size, rating and architecture for the next stage of work. A system with a total rating of 50-75kW is planned for direct integration, demonstration and rig testing. The plan for this work embodies all elements of the next stages of work to develop and demonstrate a full Quantor system to the point where it will be ready for an at-sea demonstration.

The plan includes parallel development of the components for a megawatt-scale system that will ultimately allow a larger system offering.