Blue Power Energy Ballscrew PTO

WES Power Take Off
Stage 2 Project
Public Report

Blue Power Energy Ltd

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

Blue Power Energy is developing a novel power take-off (PTO) technology for wave energy converters (WECs). The concept is based around the use of ballscrews to convert linear input motion (as is typical from many wave energy converter concepts such as heaving buoys) to rotary output motion, suitable for conventional electrical generators. In this application the ballscrews are said to be “back-driven”, with manufacturer’s data suggesting that mechanical efficiencies of the order of 90% are achievable in this drive configuration.

Prior to the Stage 2 project, Blue Power had tested six PTO units in various scales and configurations. Two units were mechanically characterised at the Hydraulics and Maritime Research Centre at University College Cork, using a small DC generator and a range of resistive loads to represent output load conditions. A subsequent scale model was fitted to a heaving buoy WEC and tested at the University of Strathclyde towing tank using a similar setup for loading. Additionally, some rudimentary real-world testing was conducted with a pier-mounted PTO, driven by an oscillating float via pulleys. This work proved that the PTO concept was practical, but was not sufficient to assess the overall technical and commercial viability of the device.

The purpose of the Stage 2 programme was therefore to tie the existing work together and assess the performance, reliability, affordability and Levelised Cost of Energy (LCOE) of the technology in line with WES’ objectives.

Energy Technology Centre was extensively involved in delivering the work packages, working as a contractor to Blue Power Energy. Amongst other aspects of the programme of work, ETC staff undertook all electromechanical testing of the PTO at ETC’s facilities.

The project team was therefore a combination of Blue Power and ETC staff. Brief biographies are provided in the following paragraphs.

Conor Haughey, BSc **Director, Blue Power Energy**

Conor is a professional engineer with key sector knowledge and a proven track record of developing successful businesses and engineering projects. He previously held the position of project manager for the development of the 350 berth marina located at Malahide, Co. Dublin, which includes a heavy duty floating breakwater system to protect against wind generated waves within the estuary, a 650 metre long seawall, boat storage areas, mobile boat hoist, marina clubhouse and marina related retail facilities. Amongst other significant interests, Conor is co-founder and shareholder of One 4 All Ltd, a multinational company selling multi-store gift cards with an annual turnover of £155 million. In 1988 Conor founded Feltrim Mining plc, a mineral exploration company which was floated on the Irish and UK stock exchanges. Conor’s vision for an Irish wave energy company and market was the catalyst for the design and development of Blue Power Energy’s technology. Conor holds a Bachelor’s Degree in Science and Mining Engineering from the Michigan Technological University, USA. He is Chairman of the Irish Wave Energy Developers Association.

Colin O‘Brien **Mechanical Design Engineer**

Colin has designed and supervised the building of all Blue Power PTOs to date. Colin is an award winning mechanical engineer, taking third place in the Irish Young Engineer of the Year Award (Siemens Prize) awarded by Engineers Ireland. Colin has expertise in system integration between the mechanical and software aspects of a sytem; previous work having included the development of a remotely operated magnetic drive medical pump for Olympus KeyMed.

Kevin Farrell, BEng **Engineer, Blue Power Energy**

Kevin has spent the last year working as a mechanical project engineer for Blue Power Energy on the WES stage 2 PTO project. He supported the mechanical design of the prototype and the completion of project deliverables, as well as additional project management duties.

Kevin's earlier experience lies in the design and manufacture of cargo carrying units (CCU'S), pressurized tanks and intermodal equipment (i.e. ISO and Offshore portable tanks) for the offshore oil and gas industry.

He also worked as an appraisal engineer for the firm who manufactured this equipment, where he was the point of contact for any inspection queries from the third party surveyors and ensured that the products were designed and built in compliance with the relevant codes, standards and legislation. He liaised with the relevant approval bodies (DNV GL, Bureau Veritas, Lloyds register etc.) to obtain the relevant approvals and certification (DNV 2.7-1, ASME U-Stamp, PED etc.).

John Bingham, BSc, PhD **Director, Energy Technology Centre**

Building on a career spanning engine development, thermal systems technology and power generation, John is a director of Energy Technology Centre which is focused on innovation and development in renewable energy systems. He has extensive experience in planning, managing and delivering engineering development projects on energy devices, including component and system development of marine power devices and wind turbines. Previous experience included divisional management responsibility at the National Engineering Laboratory (now TUV SUD UK) for IC Engines Centre, Thermal Engineering and Low Carbon Technologies.

Tom Clark, BSc **Principal Engineer, Energy Technology Centre**

Tom's particular expertise is in bespoke test rig design, build and operation. His career has covered a wide range of projects requiring expertise in mechanical, thermal and electrical design and associated instrumentation. Recent experience has focused on component testing for marine power systems, development of wind turbines, implementation of a large thermal test facility (4MW) for developing energy recovery systems and developments related to combustion systems. This expertise has been built on an earlier career covering turbomachinery, engine development, heat transfer and textile machinery.

Euan McPherson, MEng **Project Engineer, Energy Technology Centre**

Euan is a versatile electrical and mechanical engineer whose professional career commenced with a wave power company where he undertook scale model development projects at the Herriot Watt University wave tank, University of Strathclyde towing tank, MARIN (Netherlands) and Loch Ness. Past projects at ETC have included small wind turbine development and build and commissioning of bespoke control systems for client thermal plant installations.

1.2 Description of Project Technology

The Blue Power PTO is centred around the use of back-driven ballscrews to convert linear motion to rotational motion. The basic configuration of the device is shown in Figure 1. Input to the device is via the pushrod (1) which actuates the crosshead (2). The captive ballscrew nuts (3) are located in the crosshead and are drawn along the ballscrew shafts (4) by the motion of the pushrod. This motion causes the shafts to be rotated and so drive the generator (5) through suitable gearing. This gearing is driven via twin, one-way clutches (6), each arranged for the opposite direction of drive. Consequently, as the rotary motion of the ballscrew shafts slows and then reverses during each cycle of the pushrod, unidirectional rotation of the generator is maintained.

Blue Power's design intent was that the variation in rotational speed would be damped by a flywheel (7), however ETC's test work identified that the flywheel does not offer significant benefits to system operation. A photograph of the as-built Stage 2 PTO is shown in Figure 2. Note that this photograph shows the PTO at a later stage of testing, following the addition of a constraining carriage to the crosshead.

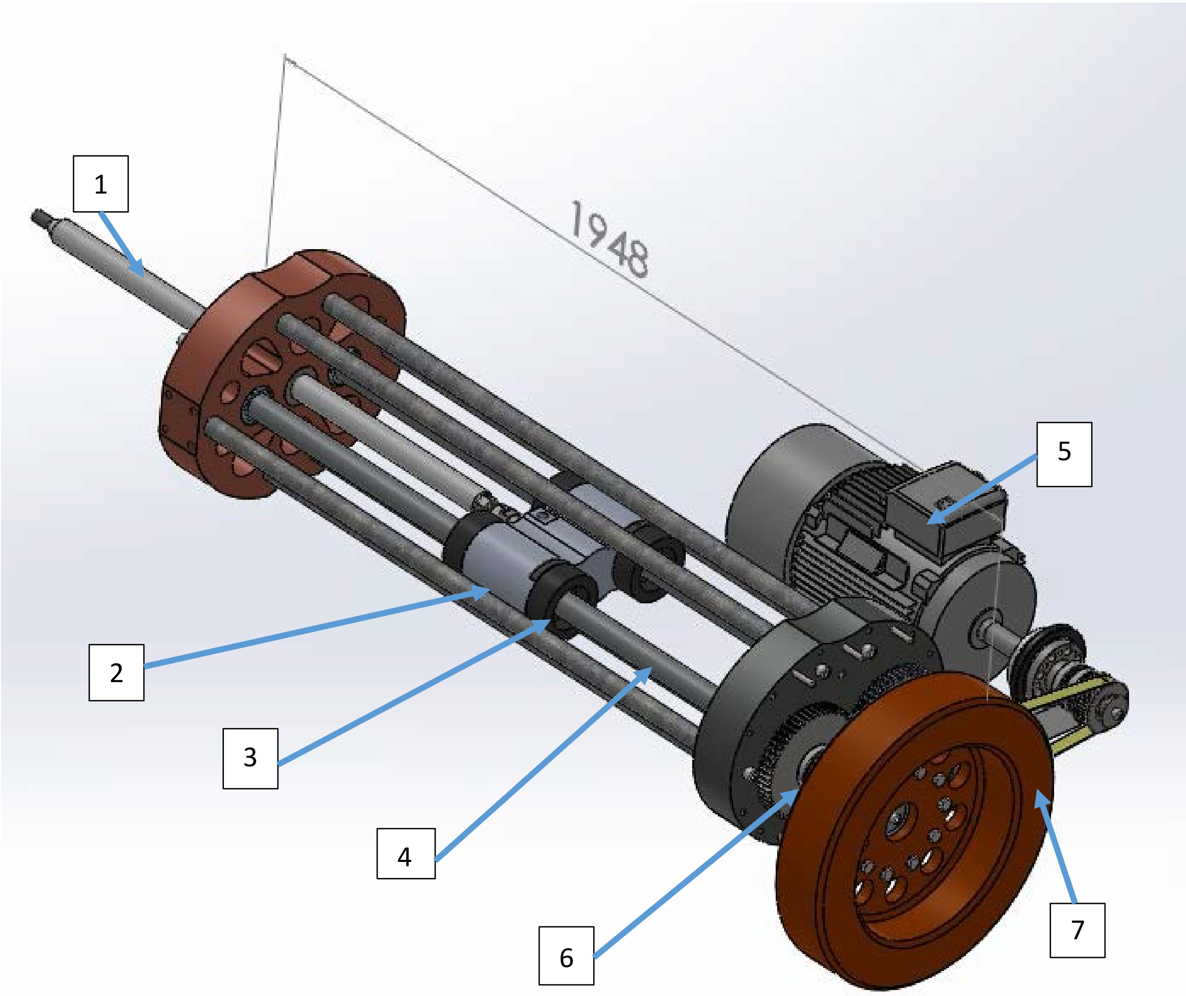

Figure 1 Layout of the Blue Power PTO

Figure 2 As-Built Blue Power PTO

1.3 Scope of Work

As noted in Section 1.1, the purpose of the Stage 2 programme was to tie the existing work together and assess the performance, reliability, affordability and Levelised Cost of Energy (LCOE) of the technology in line with WES' objectives.

There were, therefore, three primary objectives to the project:

OB1 Evaluate accurately the conversion efficiency of the PTO and then optimise the design to ensure that the best possible overall efficiency level is obtained.

OB2 Develop a control system that can tune generator output, such that energy extraction and power smoothing can be maximised over a wide range of input sea states.

OB3 Evaluate accurately the loading on the system components, and to carry out accelerated life cycle testing, in order to gain confidence in the predicted availability factors for the system.

To achieve these objectives, the following packages of work were undertaken (note that in the interests of better representing the sequence of the work undertaken, these are structured slightly differently from the project Milestones):

WP1 Design review of the prototype Blue Power PTO and production of a report suggesting improved materials, manufacturing methods and assembly methods to achieve increased cost effectiveness for volume production.

WP2 Production of manufacturing drawings and fabrication of PTO unit.

WP3 Review of available generator and inverter technologies and selection of a generator and inverter set for testing. An induction generator and inverter package was selected and then procured, assembled and commissioned.

WP4 Electromechanical characterisation of the generator and inverter on a motoring-dynamometer test rig. The results were compared with the electromechanical characterisation of a permanent magnet generator, resulting in the conclusion that the flatter efficiency characteristics of the permanent magnet generator were more suitable for the Blue Power PTO.

WP5 Design and commissioning of a bespoke mechanical test rig (Figure 3) and subsequent mechanical characterisation of the PTO (OB1). The test work concluded that the mechanical efficiency of the PTO was strongly dependent on output load but relatively insensitive to stroke, period or system inertia. It was also noted that the flywheel mass required to achieve the desired degree of output power smoothing gave rise to excessive peak loading of PTO system components, therefore the flywheel offers no significant benefits to system operation.

WP6 Production of a dynamic simulation model in the Solidworks software environment to allow the calculation of component loads and verify the outputs from the test rig. Additionally an energy simulation model was built to examine the power smoothing characteristics and energy balance of the flywheel. The results from the models confirmed the conclusions regarding the flywheel from WP5 and showed that the phasing of the flywheel energy inputs and outputs would not result in improved PTO operation.

WP7 Design, production and testing of a load control system to allow the PTO to operate at the point of maximum mechanical efficiency for a given input wave height and period. The system was based on an off-the-shelf industrial programmable logic controller (PLC). The system monitored the output from a linear displacement transducer to detect the input wave conditions and set the generator load according to the point of maximum efficiency identified in WP5 (OB2).

WP8 Development of a procedure for PTO performance prediction under different applications. This procedure can be employed for future development to determine the optimal WEC characteristics (such as ballscrew pitch) for a given deployment site.

WP9 Loading evaluation and physical endurance testing. Physical endurance testing conducted on the hydraulic test rig was compared with the results from the dynamic simulation model developed in WP6. The model was setup to provide key component loads for the PTO rated output power. The simulation outputs were used to determine component lifetimes based on manufacturer's data and calculation tools. The ballscrews did not exhibit any damage under endurance testing. Recommendations regarding the ballscrews, sprag clutches and bearings were made based on the calculated service lives. (OB3).

WP10 Production of a commercialisation roadmap and a techno-economic study covering the long term commercialisation plans for the PTO and Levelised cost of Energy Predictions. A Front End Engineering Design Study for entry to Stage 3 of the WES PTO development programme was also produced, including preliminary design and fabrication plans and the preliminary monitoring and test plan.

Figure 3 Bespoke Hydraulic Test Rig with Blue Power PTO

1.4 Project Achievements

The mechanical efficiency of the PTO was mapped on a bespoke test rig for various stroke length and wave frequency inputs. Mechanical efficiencies of up to 90% were measured on the test rig. The mechanical efficiency was found to be strongly dependent on output load, but was relatively insensitive to stroke length, period and system inertia. This is highly advantageous for PTO operation, as it means that the mechanical efficiency is relatively insensitive to the type of wave inputs applied. The output load can be readily adjusted by the load control PLC, which issues a load demand signal to the four-quadrant inverter. The inverter is the interface between the electrical generator and the electrical grid.

The ballscrew performed well under test, exhibiting no visible wear after more than 50,000 cycles under various load conditions. This enhances confidence in the use of ballscrews for wave energy devices and makes them an attractive option for converting linear motion to rotational motion in practical power take-off systems. The PTO was constructed largely using standard components. Given that many of the key items including the ballscrew, generator and sprag clutches are standard parts, the PTO system benefited from market competition between suppliers and circumvented additional research and development associated with bespoke linear generator arrangements. This modular approach is also highly beneficial with respect to the scalability of the system. Components are available in an array of sizes and the costs of scaling up the PTO are more easily predictable. The ballscrews are more economically viable at larger scale.

Between the mechanical characterisation of the PTO [WP5] and the programme of endurance testing [WP9], valuable operational experience was gained regarding the structural behaviour of the PTO. The need for some key mechanical and structural improvements was identified, particularly relating to the clutch sizing and mounting methodology. One set of sprag clutches failed during mechanical characterisation of the PTO, however the larger capacity replacement clutches survived the endurance testing. Flexing of the PTO support frame was observed under test, leading to the finding that a guiderail is required to prevent rotation of the crosshead in future PTO designs. Both of these findings confirm the conclusions of the design review [WP1], and are easily addressed by straightforward mechanical and structural design changes for the next generation of Blue Power PTO.

One of the most important findings from the Stage 2 project is that better energy capture is achieved and peak mechanical loads are reduced when the inertia of the dynamical system is minimised. This finding arose from development of the flywheel energy model and was reinforced by the results from physical testing. The components can be therefore be specified for a less arduous duty. Down-sizing the components and structural items and removing the flywheel has obvious advantages with respect to cost of production. By way of example, the flywheel of the Stage 2 PTO accounted for approximately 9% of the total mechanical component costs.

A knock-on effect from minimisation of system inertia is that the rotational velocity of the output shaft is highly variable. The combination of generator and inverter was selected under the assumption that the flywheel of Blue Power's PTO would be subject to relatively small speed variation under load. That is, the speed observed would be approximately constant with some ripple. Post sales discussions with the inverter vendor have identified that such wide speed variation requires extensive R&D effort to optimise system functionality. This finding constitutes another important learning outcome, namely that permanent magnet generators are more suitable for the Blue Power PTO.

The use of standard parts has allowed the PTO to achieve predicted full scale CAPEX and OPEX that are within WES' expectations for devices at Stage 2. The design review and the findings from the testing have identified significant improvements and methods of reducing manufacturing costs. This allows the LCOE of a projected full scale Blue Power PTO to be reduced to the extent that it is nearly within WES' long-term targets. It is anticipated that the Stage 3 development programme will further reduce the costs such that the LCOE is within the target.

1.5 Applicability to WEC Device Types

The Blue Power PTO is a generic device by design, thereby qualifying it as suitable for combination with a range of WEC technologies. In the long term it is envisaged that the Blue Power PTO will be akin to a 'catalogue' item that can be fitted to applications where reciprocating wave motion input is to be converted to electricity generation in a rotating machine. A non-exhaustive list of broad WEC categories to which the Blue Power PTO may be applicable is presented below.

Attenuator

The attenuator type WEC is a device that captures energy from the relative motion of two or more floating hinged components which operate by riding the waves parallel to the predominant wave direction. Figure 4 shows Blue Power PTOs fitted to a conceptual attenuator type WEC, illustrating how linear motion may be extracted from this type of device for energy conversion via the Blue Power PTO.

Point Absorber

A point absorber WEC captures energy from all directions at the water surface via a floating structure. The relative linear motion between the floating structure and fixed base are converted to electrical power via an appropriate power take off system. There is a variety of point absorber designs with different configurations of displacers and reactors and consequently differing degrees of freedom. A conceptual arrangement of Blue Power PTOs incorporated into a two- body point absorber is illustrated in Figure 5.

Oscillating Wave Surge Converter

Oscillating wave surge converters absorb energy in the surge degree of freedom at shoreline and near shore locations. The WEC oscillates back and forth like an inverted pendulum mounted on a pivot (free body diagram shown in Figure 6).

There are several methods available to utilise linear motion in this WEC via different mechanical linkage configurations.
Figure 6 shows one example configuration that may be used for extracting power via linear motion. The Blue Power PTO can be configured to convert this linear motion to rotary motion.

Bristol Cylinder

The Bristol cylinder WEC is a near shore device which comprises a fully submerged buoyant cylinder tethered to the sea bed by a simple mooring system which permits coupled surge and roll motions of the cylinder. Appropriate connections of the mooring lines to the Blue Power PTO could extract linear power from the system (Figure 7).

Other Multi-Mode Absorbers

A device capturing energy via the motion of an outboard buoyant chamber relative to some fixed or floating structure would be suitable for the Blue Power PTO. Conceptual arrangements are shown in Figure 8 and Figure 9. Multiple floats/PTOs could be used as illustrated in Figure 8. The floats could utilise independent generators, or be meshed to a single larger generator.

Since the Blue Power PTO has been intentionally designed as a generic power take-off item, no one WEC type is necessarily preferred over another with regard to functionality. However it could be argued that a point absorber is perhaps the simplest WEC type to develop, having been the subject of extensive study in the literature. In addition point absorbers tend to be best deployed in farms of large numbers of units with relatively low nameplate power ratings, apt for Blue Power's current stage of development. It is also possible that WEC types incorporating several Blue Power PTO units provide a greater degree of intrinsic electrical smoothing, as would be the case with a number of point absorbers connected to a central grid-tied regenerating inverter.

To this end Blue Power has engaged with a developer of a multi-mode point absorber capable of incorporating multiple Blue Power PTO units. For reasons of commercial sensitivity the developer cannot be named in this report, however Blue Power's WES Stage 3 bid will be focussed on integrating the PTO with the specific device. It is envisaged that individual full scale PTO units for WEC integration will have nameplate capacities of the order of 100kW.

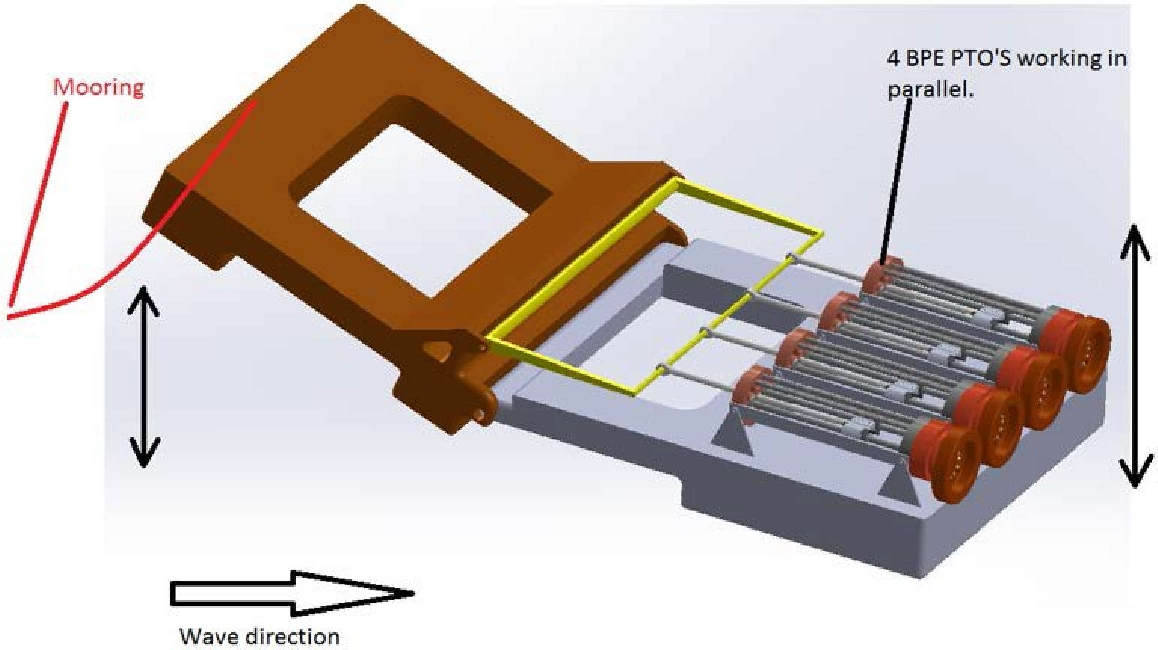

Figure 4 Conceptual Attenuator Type WEC Fitted With Blue Power PTOs

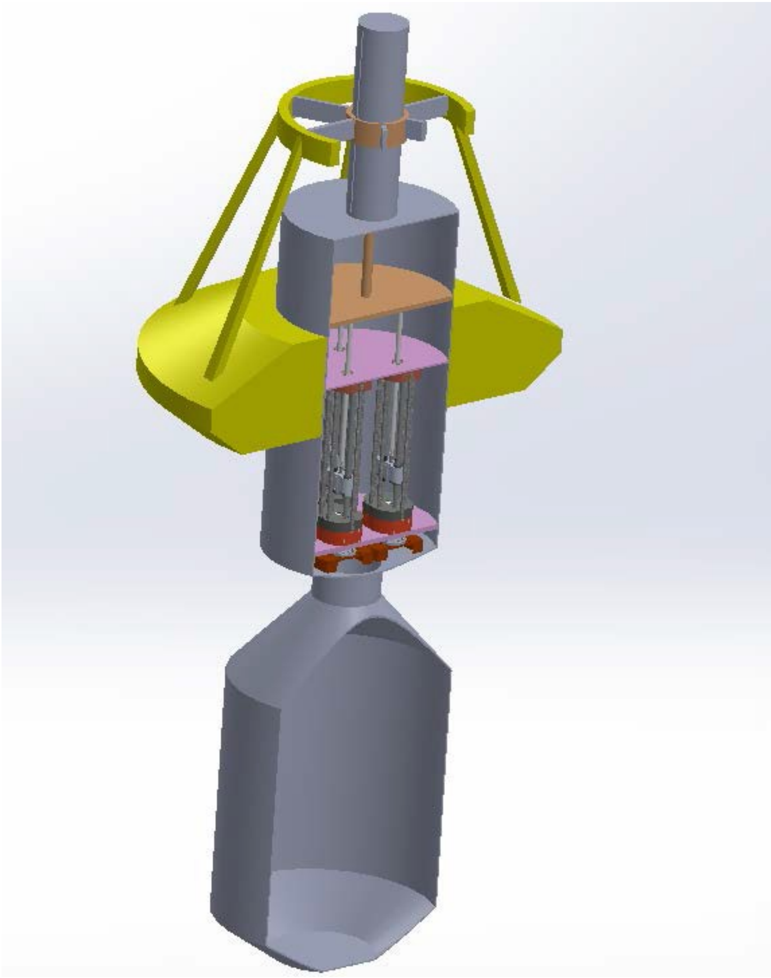

Figure 5 Conceptual Point Absorber WEC Fitted With Blue Power PTOs

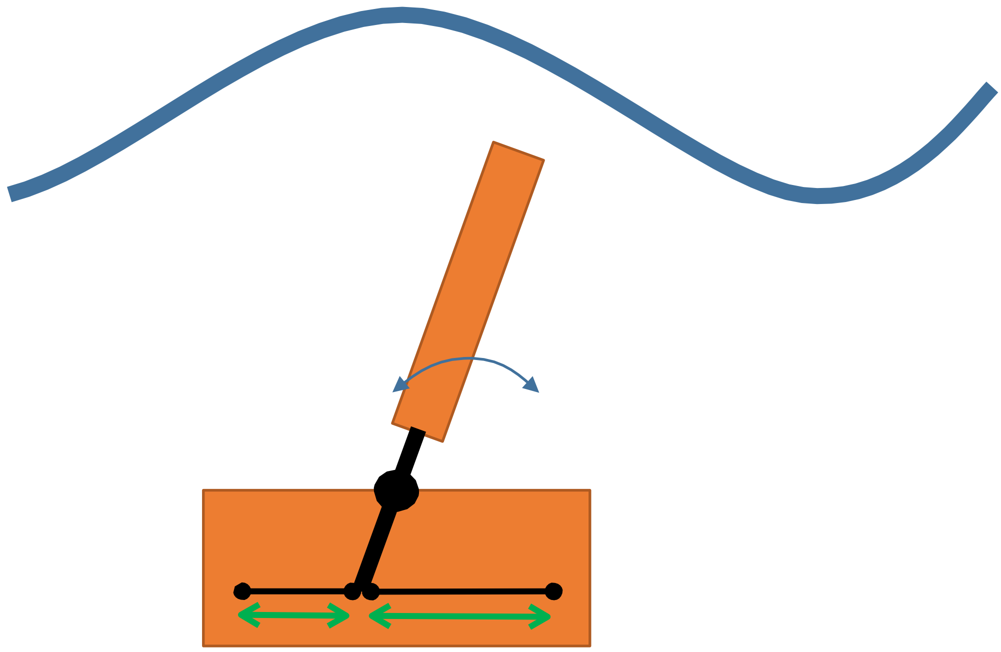

Figure 6 Free Body Diagram Of Oscillating Wave Surge Converter

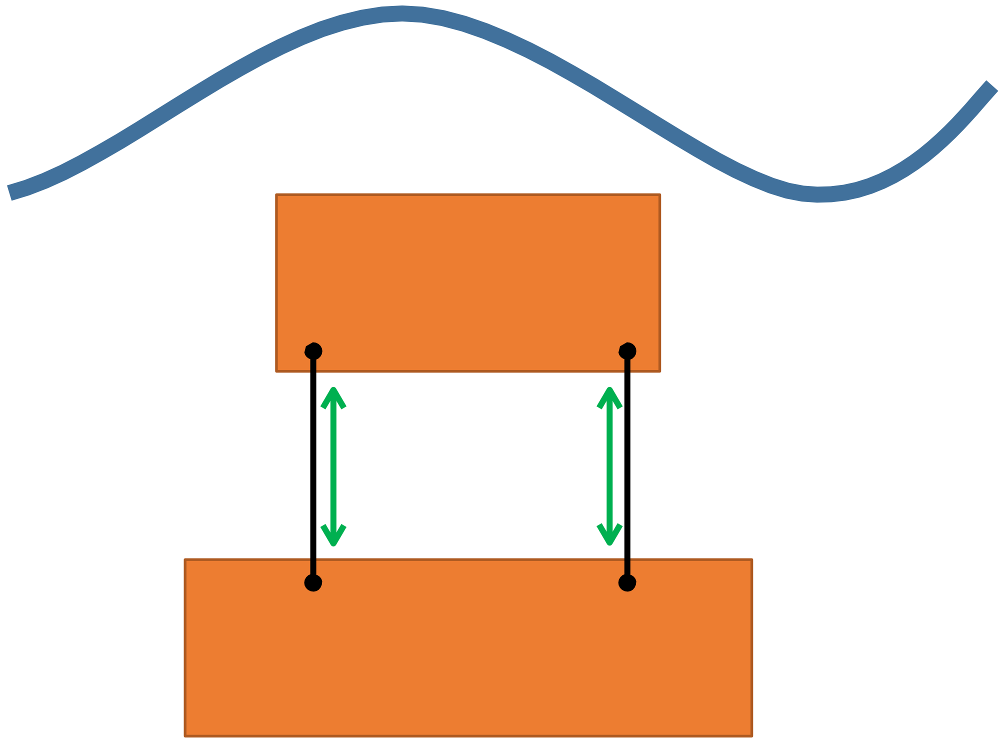

Figure 7 Free Body Diagram Of Submerged Pressure Differential Type WEC

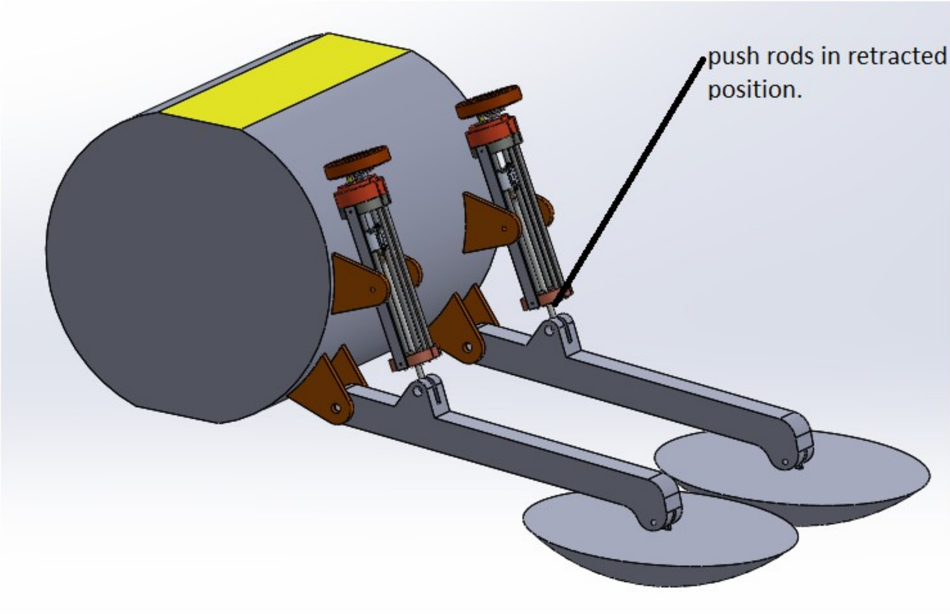

Figure 8 Multi Mode WEC

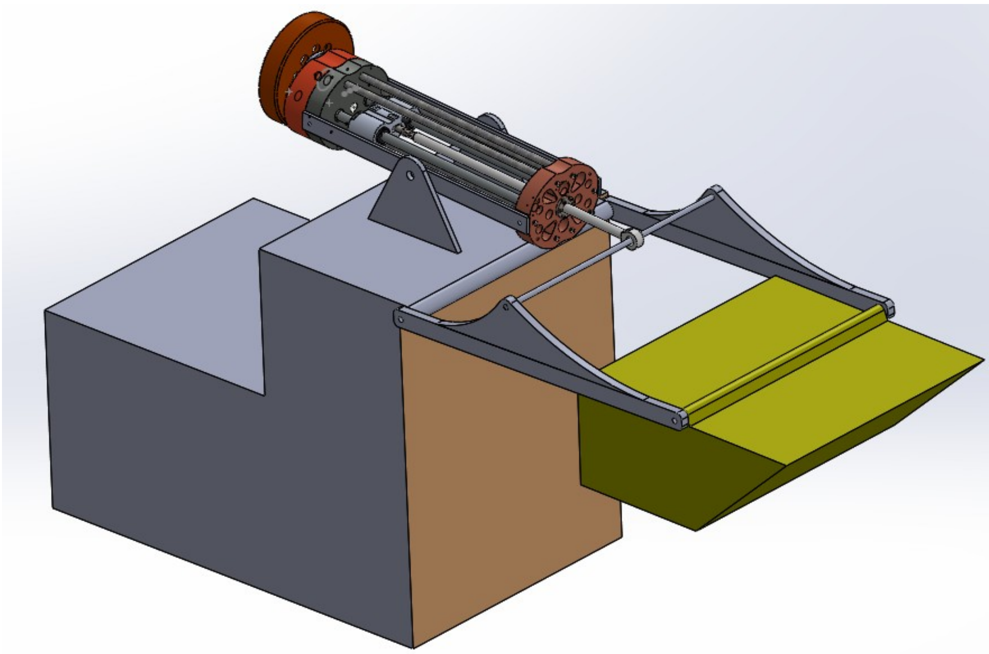

Figure 9 Combined Heave-Surge WEC (Seawall Mounting Shown)

1.6 Summary of Performance against Target Outcome Metrics

Affordability

As noted in Section 1.4, one of the strengths of the Blue Power PTO lies in the adoption of standard components. Unlike magnet-stack linear generating technologies, the PTO can be used with many suitable off-the-shelf conventional generators from different manufacturers. Of the components which are bespoke, such as the gear case and clutch housings, the learning from the Stage 2 project has identified significant methods of cost reduction by adoption of cheaper manufacturing methods. The LCOE of the projected full scale device (100kW) is close to WES' long-term LOCE objective.

Performance

As noted in Section 1.4, mechanical efficiencies up to 90% were measured during PTO mechanical characterisation. Generally the mechanical efficiency of the PTO was found to increase with the applied load. In terms of electrical generator output, the Blue Power device is highly advantageous in that the desired generator efficiency characteristic can be chosen to match a particular WEC characteristic (velocity/force profile resulting from the WEC design and any applicable linkages) by choosing between different off-the-shelf generators.

Availability & Survivability

After replacing the failed sprag clutches with larger models, the PTO was available to complete the rest of the test programme, including the endurance test. Straightforward design changes to the sprag clutch housing will improve the PTO availability. Torque limiting devices may be applied to future PTOs in order to further improve survivability without having to over-engineer structural components. The addition of a guide rail to prevent crosshead angular deflection in future PTO designs is also expected to make the PTO more robust. The findings from the Stage 2 programme have therefore had a clear impact on WES' availability and survivability metrics.

1.7 Communications and Publicity Activity

The following media have been used for promotional purposes and are referenced in Section 1.9:

- Blue Power A2 poster (displayed at WES workshop)
- Blue Power Energy PTO slides (presented at WES workshop)
- News bulletin on Blue Power Energy Website

1.8 Recommendations for Further Work

Ballscrew Testing

The Stage 2 work made a strong case for the employment of ballscrew drives in wave energy converters. However it became evident that ballscrews are typically used in high-precision applications and manufacturer's lifetime data typically relates to loss of positional accuracy rather than mechanical failure. Furthermore, the study was conducted using a single ballscrew, which may have had sub-optimal parameters (especially lead angle) for wave energy applications.

It is proposed to procure a number of ballscrews covering a spread of technical parameters and manufacturers. A bespoke test rig will be constructed to investigate the axial force, torque and frictional characteristics, which will be compared to manufacturer's data. Following initial testing, the ballscrew selection will be narrowed to the most favourable for wave energy conversion. Endurance testing to failure will commence using the chosen ballscrews. This package of work specifically relates to the Availability and Survivability WES metrics, as it will allow the anticipated time to failure to be quantified.

Coupled PTO-WEC Tank Testing

The integration of the PTO into a WEC is critical, since the economic case for the PTO at this stage is highly influenced by the performance and O&M characteristics of the WEC to which it will be deployed. As noted in Section 1.5, Blue Power will be working with the developer of a multi-mode point absorber for the WES Stage 3 bid.

In the first instance it is proposed to study the coupled WEC-PTO behaviour by tank testing an existing 1/20 WEC scaled model, fitted with newly designed Blue Power PTO models. This test programme will require initial design of the mechanical linkage between the PTO and WEC. The outputs from this test will allow the dynamical aspects of the Blue Power PTO to be investigated subject to the complex force coupling of the WEC and PTO.

PTO Upscaling

Alongside the coupled PTO-WEC tank testing, it is necessary to bring the PTO in line with the recommendations made during the Stage 2 work, at a scale that is representative and can inform the design of the commercial product. The PTO scale will be carefully chosen such that it is appropriate for real world testing of the WEC at EMEC's Scapa Flow wave test site, under a Stage 4 WES programme. The PTO will be designed, constructed and commissioned under the Stage 3 programme of work. The device will benefit from the structural recommendations from the Stage 2 work; for example appropriate frame stiffening will be employed and a cross-head guiderail will be installed.

Coupled PTO-WEC Real World Testing

A programme of real-world testing at the European Marine Energy Centre's Scapa Flow wave test site will bring together the outputs from the Ballscrew Testing and Coupled WEC-PTO Modelling. This test will provide valuable real-world operational experience relating to marinisation of the PTO and the marine operations required for deployment and commissioning. In addition, operational data in real seas will produce reliable performance predictions, supporting robust estimates of LCOE.