SEÒLTA

Survivable and Efficient OLeo-hydraulic assisted power TAke-off (SEOLTA)

WES Power Take Off
Stage 1 Project
Public Report

Fundacion Tecnalia
Research & Innovation

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

Description of the technology idea

The main goal of this project is to provide a step change in the overall performance of Power Take-Off (PTO) systems used for Wave Energy harvesting. Particularly, this project has characterises and assessed the feasibility of a novel electric-hydraulic hybrid Wave Energy Converter (WEC) PTO. Such technology has previously been used to achieve significant reductions in fuel consumption in the automotive sector.

This novel PTO project addresses one of the underpinning problems of wave energy: its fluctuating nature with a high peak-to-average load ratio. This concept also demonstrates a technology transfer of hydraulic hybrid power trains from the automotive to the wave energy sector.

The proposed solution is a combination of two main systems, an electric PTO and a hydraulic PTO. The electric PTO transforms energy in the most efficient manner, whilst the hydraulic systems provide an effective way for short term energy storage. This way, the hybrid PTO can smooth incoming energy fluctuations without compromising the conversion efficiency.

Project team

This project phase has been executed by TECNALIA, an applied research and technology development centre, and OCEANTEC, a dynamic Wave Energy Technology developer. TECNALIA acted as project manager and led the technical activities. OCEANTEC contributed to the technical activities and provided the underpinning IPR, stochastic wave-to-wire modelling tool and technical specification of its WEC for the case study.

TECNALIA (http://www.tecnalia.com) is the first privately funded applied research and technology development centre in Spain and one of the leading such centres in Europe. We transform technology into GDP, improving people's quality of life by generating business opportunities for companies with a multi-sectorial and multi-technology approach. TECNALIA employs 1,400 people (179 PhDs), has a turnover of €100m and a network of 4,000 clients. The current project has been carried out by the Marine Energy Department of the Energy and Environment Division. This Department is mainly focused on modelling, analysis and optimisation of floating structures and mooring systems; modelling of electrical sub-systems and development of grid connection solutions; analysis of power quality and grid code compliance; corrosion monitoring, materials testing and failure analysis; simulation of installation, operation, maintenance and decommissioning strategies; resource and environmental impact assessment.

OCEANTEC (http://www.oceantecenergy.com) is a private SME, founded in 2008 by TECNALIA and IBERDROLA as main partners, committed to generate major impacts in economic terms, by means of innovation and technological development focused on the wave energy sector. OCEANTEC's skills and experience include: Technological development; Site selection and resource energy analysis; design, construction and installation of prototypes; Project Management; Testing, control and technical evaluation of on-site tests; Optimisation of energy costs; Commissioning and operations.

In 2010, OCEANTEC strengthened its company resources and strategy, and set up the development of a second novel wave energy harvesting technology which aims to position the company as a leading technology provider in the near future. The design of this new wave energy converter has been validated in two comprehensive wave tank testing programmes (2012 and 2013). OCEANTEC is currently preparing the manufacture of a reduced power prototype for deployment at sea in the summer of 2016.

Measures of project success

The novel PTO is expected to make a positive impact on long term reduction of the cost of wave energy. This ultimate requirement will be realised through different contributions to the performance, survivability, availability and affordability. These are in fact the basic requirements of the proposed solution.

Performance and survivability are the primary focus of this project (disruptive metrics), whereas availability and affordability (incremental improvements) have only been estimated, since they will only be adequately assessed in later stages of development.

The main target outcomes are as follows:

- Performance. Higher electrical conversion efficiency .
- Survivability. Lower maximum to average load ratio in the generator for the most energetic sea state.
- Availability. Higher PTO reliability and lower production losses during the period from PTO breakdown to replacement.
- Affordability. Lower PTO operating cost due to longer maintenance intervals and lower generator repairs and replacements.

1.2 Description of Project Technology

Wave energy is a fluctuating power source with a high peak to average ratio. Next picture shows the typical power fluctuations over time for both the hydrodynamic and the prime mover power. The mean power is also depicted.

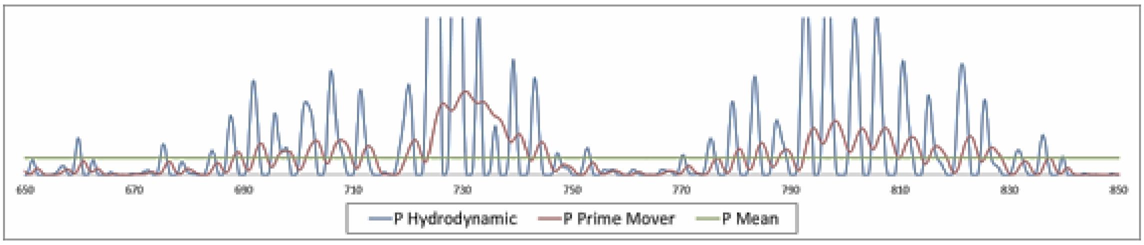


Figure 1.1: Example of power fluctuations over time.

As a result from this, electrical PTO components usually need oversizing to absorb energy peaks, result in lower average transformation efficiency and power output replicates input fluctuating patterns. Traditionally, hydraulic PTOs have been used to overcome this problem since performance is less sensitive to partial loading and provides storage to smooth input fluctuations. However, it adds more transformation steps that decrease total efficiency.

The novel PTO configuration is based on a background know-how and European patent filed by OCEANTEC in 2015 [1]. Performance assessment methods and particularly OCEANTEC's stochastic wave-to-wire modelling tool is another relevant background intellectual property.

[1] M Ojanguren et al, 2015. Electric-Hydraulic Hybrid Power Take-Off with Application to Renewable Energy Conversion -

EP15382569 (not published yet).

The invention is essentially a combination of two main systems, namely an electric PTO and an oleo-hydraulic PTO. The electric PTO transforms energy in the most efficient manner, whilst the hydraulic systems provide an effective way for short term energy storage. This way, the hybrid PTO can smooth incoming energy fluctuations without compromising the conversion efficiency.

The electrical PTO comprises at least a conventional electric generator (G), and may also include power electronics and a transformer in order to accommodate electric output parameters to the grid connection requirements. The electric generator is linked to the prime mover (P) that captures incident wave energy.

On the other hand, the oleo-hydraulic PTO comprises a variable displacement pump (H) attached to a number of high pressure (HP) and low pressure (LP) accumulators depending on the energy storage needs.

As it is shown in the schematic below, the electric generator is connected in parallel with the variable displacement pump so that they can act on a common rotating shaft either adding or subtracting their respective torques according to the control mode.

A control unit (C) sets the values of the torque in the electric generator and variable displacement pump according to the intended objective.

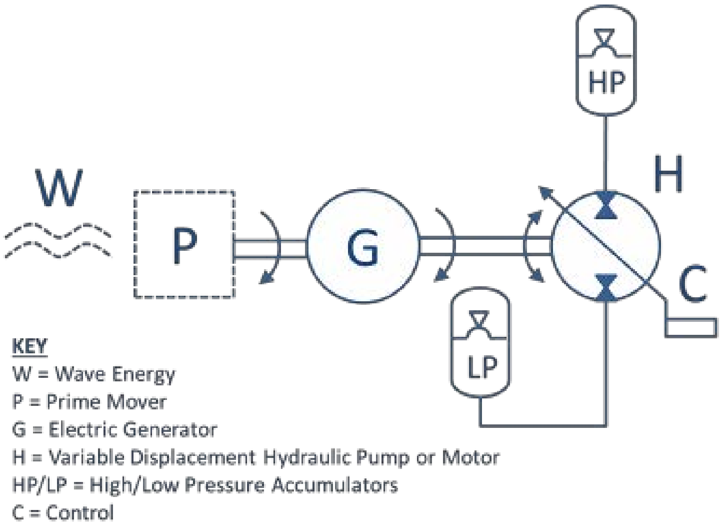


Figure 1.2: Schematic of the novel PTO architecture

During wave energy peaks, the electrical generator and the variable displacement pump add their resisting torques in order to store excess energy, whereas in conditions below the average, the oleo-hydraulic system provides an active torque to compensate this shortfall in the electrical generator. These two modes are depicted in the next figure.

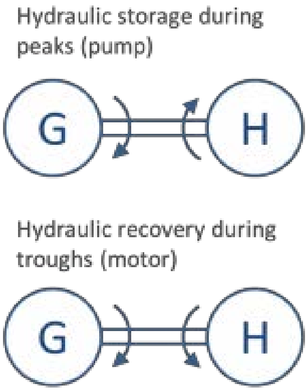


Figure 1.3: Hydraulic storage and recovery

In the context of this project, "in parallel" means that the electrical generator and the variable displacement pump are synchronised according to rotational speed (i.e. constant rotational speed ratio) but their respective torques change over time both in magnitude and direction (i.e. the torque ratio is not predefined).

The physical realisation of this parallel configuration can be done mounting the electrical generator and the variable displacement pump:

a) on the same rotating shaft (i.e. 1:1 ratio), or
b) by means of any particular gearbox arrangement (i.e. 1:x ratios)

as depicted in the following figure.

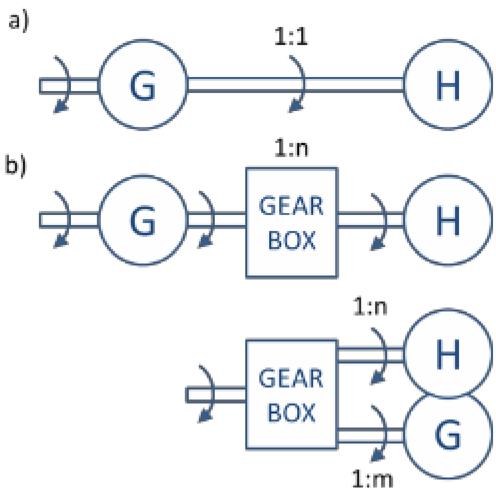


Figure 1.4: Alternative PTO parallel configurations.

The proposed PTO system can open the way to a wider working range for wave energy converters: in moderate sea states as well as in more extreme conditions. The hybrid PTO allows implementing a less expensive generator with higher transformation efficiency in a wider range of sea states. The capacity factor of the generator is also expected to increase as its rated power can be lower due to the protection afforded by the hybrid PTO. Moreover, the loading on the components will be smoothed, contributing to a step change in the sector. The capability of achieving lower loading levels can be further enhanced considering advanced control strategies.

Finally, it should be considered that even though the present technology is at an initial verification stage, the individual components on which is based have been adopted widely in other sectors and previous experience in the automotive industry application, exhibiting good operational performance and reliability.

1.3 Scope of Work

As it has been already mentioned, the objective of the project is to assess the advantages of the novel PTO system for different WEC device families, its long-term impact on LCOE reduction, and demonstrate the benefits of its implementation in a floating OWC system. In order to achieve this objective, a work plan structured in five work packages was proposed. The work plan involves the following types of activities:

- Idea and design development
- Methodology
- Simulation
- Market
- Other: Project management

WP1: Concept engineering - Idea & design development

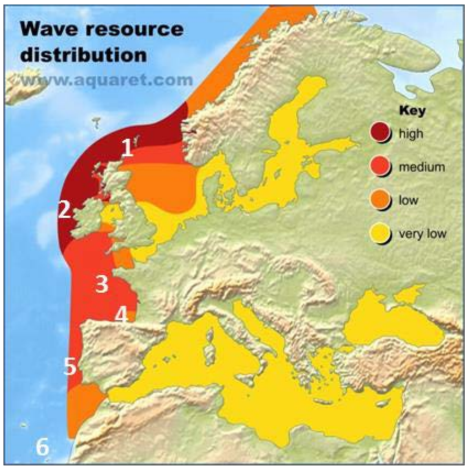
The main objective of this work package was to collect and analyse the functional requirements of the novel PTO configuration for rotating PTOs and transform them into a detailed definition of the features and key performance indicators.

This work package took as an input the preliminary analysis performed by the proponents on this concept, its alternative applications for different WEC device families, initial risk assessment and benchmark data for conventional PTO systems.

It consisted of the following tasks and activities:

- Wave resource characterization, with a particular focus on the peak to average energy features
- Quantification of the loading regime envelope within short and long terms
- Applicability to wave energy sites and WEC device families of the novel PTO.
- Data collection on commercial components: suppliers, technical specifications, costs and scalability.
- Operation and maintenance issues: critical failure modes, site accessibility and environmental factors.
- Description of relevant target outcome metrics: performance, survivability, reliability and affordability.

1	EMEC (Scontland)
2	Belmullet (Ireland)
3	SEM-REV (France)
4	BiMEP (Spain)
5	Lisboa (Portugal)
6	Gran Canaria (Spain)
7	Canada
8	Oregon (US)
9	North California (US)
10	Hawaii (US)
11	South Africa
12	South West Australia



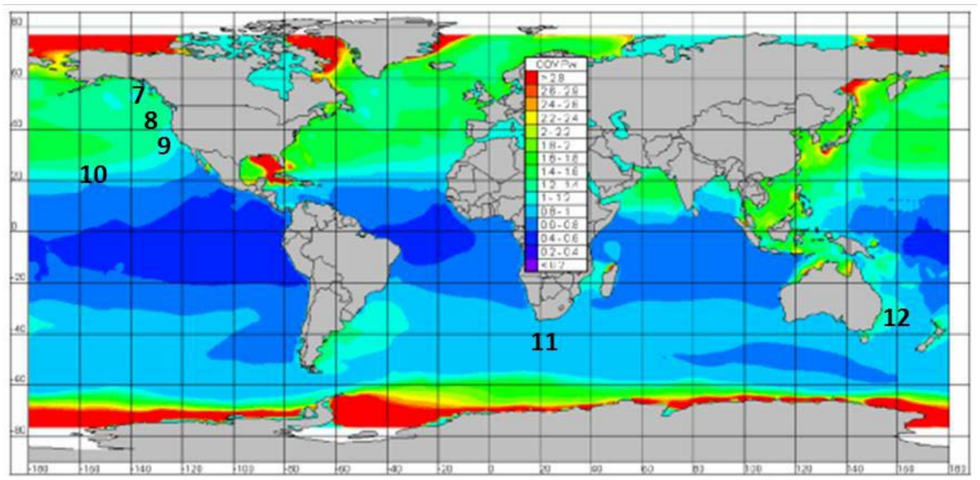


Figure 1.5: Global distribution of wave power annual variability and selected sites.

WP2: Modelling of hybrid hydraulic PTO - Methodology

This work package takes WP1 results as an input. Also, OCEANTEC provided the stochastic wave-to-wire modelling tool, to define different wave energy spectra, hydrodynamic responses, prime movers, electrical generators and power electronics.

Based on stochastic wave-to-wire modelling tool from OCEANTEC, the performance model of the hydraulic hybrid PTO has been integrated in this work package. Simulations were carried out under different loading regimes and dimensioning methodology for the proposed PTO was introduced.

To address OPEX and CAPEX metrics techno-economic approaches were also introduced and a basic model was built to enable the calculation of the final LCOE of applicable devices.

This work package consisted in the next activities:

- Hydrodynamic modelling approach proposal considering hypotheses and applicability
- Hydraulic PTO system modelling approach introduction as well as hypotheses and applicability
- Combined model building addressing both hydrodynamics and hydraulics. Limitations of the combined model and simulation conditions.
- Items considered for the economic modelling introduced and model being built. Its scope of application and uncertainty ranges are introduced.
- LCOE computation methodology mixing both performance and economic models from previous tasks.

WP3: Application to a particular WEC: OCEANTEC - Simulation

The objective of this work package was to quantify the LCOE reduction potential of the novel PTO, based on the tools defined in WP2 and the specifications of the OCEANTEC floating OWC technology. To carry out the computation of the final LCOE a near optimum sizing of both the hydraulic and the generator were required. Optimum sizing was based on minimum LCOE for a defined site given by WP1. Once this baseline scenario was set, absolute levels for the Target Outcomes were calculated and verified.

Tasks carried out within WP3 were:

- OCEANTEC MARMOK-A-5 specifications and data collection for the integration in the performance and the economic tools, as well as validation of results against bibliography.
- Model simulation computing LCOE for a range of characteristic parameters of the hydraulic system defined in WP2. Optimum sizing of the PTO.
- Selection of a suitable generator based on the power performance of the combined system and the resulting peak to mean ratio. Final specifications of the PTO and definitive computation of LCOE.
- Conclusions with respect to the baseline model.

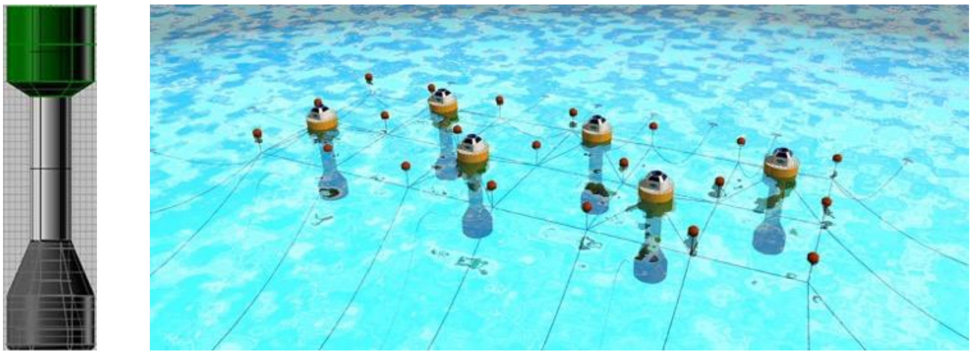


Figure 1.6: left - MARMOK-A-5 hull design; right - Artistic representation of an array.

WP4: Market feasibility - Market

The market feasibility took as input all technical results from the simulation activities carried out in the previous work packages. The main objective of this work package was to produce a final assessment of the technology based on results from simulation models and corresponding case study.

Performance and survivability were the primary focus of this project (disruptive metrics), whereas availability and affordability (incremental improvements) have only been estimated, since they will only be adequately assessed in later stages of development.

The market potential of the innovation was assessed based on the Target Outcomes and the technical risks and uncertainties.

Besides, this work package prepared the technical and non-technical activities required for taking this innovation to the market. Particularly, the commercialization roadmap and plan for the development of stage 2 were produced.

WP5: Project management - Other

Project Management deals with the role and responsibilities of the various actors and the contract with the contractor. It included the overall management, communication and coordination between the different partners, as well as the monitoring of the technical progress of the project, by means of the supervision of the achieved milestones, the management of the risks and establishment of contingency plans, as well as IPR issues.

This work package considered all contractual requirements, risk management and dissemination of lessons learned from the project.

1.4 Project Achievements

This novel PTO concept leverages on off-the-shelf components with large commercial experience in other sectors and previous experience in the automotive industry application. Individual components are at TRL9, meaning that the operational performance and reliability has been demonstrated in successive missions and the business plan is fully de-risked for large scale deployment. Hydraulic hybrid configuration for the automotive industry is at TRL7, meaning that the technology has been demonstrated in an operational environment and risks are properly managed. The novel PTO technology is at TRL3 for the application in the wave energy sector, that is, initial product verification.

In terms of functional readiness, the status after Stage 1 is as follows:

- Numerical simulation model of performance and survivability is available
- Expected life model for a single failure mode
- PTO requirements have been defined: loading regimes variability for 5 device families and different deployment sites

In which to lifecycle readiness is concerned, the status of Stage 1 is as follows:

- Site resource characterisation done
- Basic economic model to calculate LCOE available
- Affordability and availability targets estimated
- Power production/efficiency targets estimated

The underpinning technology which facilitates this solution is the variable displacement pump/motor. Overall, this novel PTO concept relies on components with large commercial experience in other sectors:

- Rotating generators: Either Squirrel Cage Induction Generators (SCIGs) or Permanent Magnet Synchronous Generators (PMSGs) are suitable alternatives. There is a large choice of off-the-shelf machines in both cases. Examples of international suppliers are ABB, Siemens, GE and Schneider.
- Variable displacement pump: The axial piston pump is the most common one, with a large choice of off-the-shelf references. A particular attention should be paid to the DDP solution from Artemis Intelligent Power, since they are also participating in another PTO project. Although a formal contact has been established during Stage 1, it was impossible to access detailed performance information to take into account this alternative. Examples of international suppliers are Parker, Bosch-Rexroth, and Eaton.
- Hydraulic accumulator: The Bladder accumulator and the piston accumulator are both suitable alternatives for its use in the hybrid PTO. Examples of international suppliers are Eaton and Parker.

The prime mover selected for the OWC device was the conventional Well air turbine. Wells turbines however experiment the stalling effect above a fixed value of the air flow rate. In practical terms, the stalling effect means that the Wells turbine will be unable to harness the most energetic peaks of wave power. This characteristic poses an important limitation on the energy capture improvement. Therefore, results obtained with the Wells turbine can be understood as a lower bound to performance improvement for the OWC family type of devices. This shortcoming can be overcome if other types of air turbines are implemented, such as the impulse and bi-radial turbines. In fact, these new turbines are promising candidates as prime movers for OWC devices.

Sites with lower capacity factors (e.g. EMEC and BiMEP) present a greater variability and therefore can be better candidates to benefit from the hybrid PTO. These sites are usually located in the Northern hemisphere and have moderate energy flux, with the exception of Belmullet (high energy site). On the contrary, sites with high capacity factors have a steadier wave energy flux and experiment less fluctuations over the year. There are usually located in the Southern hemisphere and have higher energy flux.

Site characteristics alone however have been found not to be sufficient to determine the optimum size of the generator coupled to the hydraulic system. In fact, the selection of a single value of ratio over the maximum generator power (in the fully electric version of the PTO) has provided good results for some device families, whereas for others the outcome results have even deteriorated with respect to a 100% electric PTO. However, an optimum sizing of the PTO components could lead to 50% and 100% energy production increase in a sea state with respect to the fully electrical version.

Regarding the short term storage, simulation results show that it is required a single off-the-shelf high pressure accumulator or a small array if the storage volume needs to be adjusted.

1.5 Applicability to WEC Device Types

The novel PTO is considered to be applicable to most of the WEC device families (except overtopping devices) and particularly whenever the Prime Mover includes a rotating system. Hydraulic transmissions (e.g. Anaconda) lie out of the scope of applicability of this novel PTO. This PTO could be implemented using either a rigid coupling (e.g. hinge, rack & pinion) or a self-rectifying turbine as it is described below. Results from the numerical models show that the hybrid PTO can improve both performance and survivability.

Nevertheless, as the fluctuations on the maximum to average torques are lower for device families with mechanical rectification (i.e. attenuator, point absorber, OWSC and submerged pressure differential), the hybrid PTO will be the best candidate for OWC devices.

Attenuator

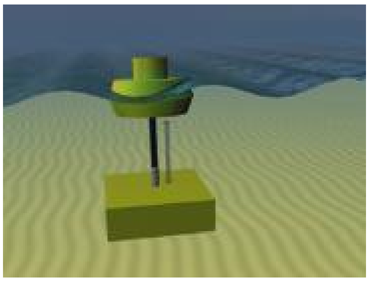
Whenever the prime mover generates a rotating torque (e.g. hinge). However the hybrid PTO is not suitable for prime movers with alternative linear movements, especially if these are based on hydraulics rams (e.g. Pelamis).

Attenuator motions are mainly static with the wave excitation while its natural frequency is located at high frequency. Then its power performance is absolutely conditioned by the excitation force amplitude curve.

Tentative list of technology developers within this device family:

Company	Model	Country	Observations
4c Engineering & Sea Power	ACER	UK	NWEC project
Mocean energy	Mocean WEC	UK	NWEC project
University of Manchester	M4 Wave Power	UK	
Crestwing	Crestwing WEC	DK	
Weptos	Weptos WEC	DK	
Columbia Power Technologies	StingRAY	US	
Grey Island Energy	SeaWEED	CAN	

Point Absorber



Single-body and 2-body point absorbers generate an alternative linear movement. This concept can be applied to rack and pinion PTOs that are able to transform wave energy into a rotating motion.

There is a subset of point absorbers that are conceptually identical to 2-body point absorbers but where the second body is a water column (i.e. floating OWC systems, which are described below).

Motions of point absorber, submerged pressure differential and OWC are very similar as long as all of them are reacting vertically against a fixed point and work actually as point absorbers due to the reduced radius with respect to wavelengths. Dimensions of point absorbers are generally selected so that the natural frequency is close enough to typical periods in a deployment site.

Tentative list of technology developers within this device family:

Company	Model	Country	Observations
Corpower	Corpower WEC	S	PTO project
Albatern	SQUID	UK	NWEC project
Laminaria	Laminaria WEC	B	
OPT	PowerBuoy	US	
WaveStar Energy	WaveStar	DK	
Wedge Global	W1	ES	
Fred Olsen	BOLT Lifesaver	NO	
40South Energy	R115	IT	
Carnegie Wave Energy	CETO	AUS	
Mermaid Power Corp	Neptune	CAN	

Oscillating Wave Surge Converter (OWSC)

These are PTOs that transform the oscillating movement around the pivot. The innovation is not suitable for PTOs with alternative linear movements, especially if these are based on hydraulic rams.

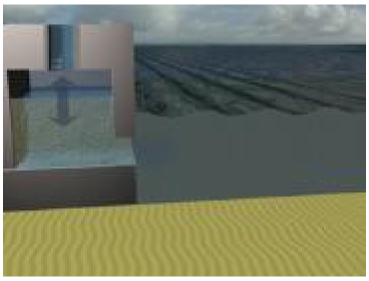
OWSCs have a frequency range at which it is very productive in terms of power performance. This range is this at which it naturally can generate waves of the same frequency.

Additionally it can be found its natural frequency in the represented frequencies as it has been tuned to low frequencies. The fact of being bottom mounted enables setting positive or negative buoyancies so that the natural frequency can be tuned to a large range of values.

Tentative list of technology developers within this device family:

Company	Model	Country	Observations
Zyba Ltd	CCELL	UK	NWEC project
AW Energy	WaveRoller	FIN	
BioPower Systems	BioWave	AUS	
Resolute Marine Energy	SurgeWEC	US	
Langlee Wave Power	Robusto	NO	

Oscillating Water Column (OWC)



The novel configuration of the PTO can be directly attached to the turbine output shaft. Usually it is used an air-turbine since the PTO components are above the water level. In some particular cases, it has been proposed to use a hydroturbine below the water surface. In both cases the concept can be applied.

Unlikewise other device family types, OWC devices are designed to operate with constant rotating velocity. This means that the torque fluctuation will be greater compared with rigid mechanical rectification. Thus, **this device family presents best in class in terms of performance for the hybrid PTO**.

Tentative list of technology developers within this device family:

Company	Model	Country	Observations
Joules Energy Efficiency Services	WaveTrain	UK	NWEC project
Oceantec Energías Marinas	MARMOK	ES	PTO project
Ocean Energy	OE Buoy	IRL	
Kymaner	Kymanos	PT	
LEANCON		DK	
Waves4Power	WaveEL	S	

Submerged Pressure Differential

This device family produces an alternating linear movement. As for the point absorber type, a rack and pinion PTO may be able to transform linear movement into a rotating motion.

Tentative list of technology developers within this device family:

Company	Model	Country	Observations
AWS Ocean Energy	AWS	UK	
Seabased		S	

Device families outside the scope of this feasibility analysis

The novel PTO system can be directly applied to a **rotating mass** that drives a rotating shaft. A variant to this device family is the oscillating mass in a **pendulum** as the SEAREV. Besides, other device hull configurations (both in size and shape) that have **water trapped inside** different chambers can be easily adapted to act as OWC systems. The relative movement between the external hull and the water body inside creates an airflow that can be harnessed using an air-turbine. One example of this new family is the UGEN floating wave energy converter.

There was insufficient information to model the response of these types of devices, however results are expected to be similar to those of point absorbers and OWC devices.

Tentative list of technology developers within this device family:

Company	Model	Country	Observations
Penguin	Wello	FIN	
ECN	SEAREV	F	
AzuraWave		NZ	
WaveTube		S	
IST	UGEN	PT	
ISWEC		IT	

1.6 Summary of Performance against Target Outcome Metrics

Performance

Reference values computed for the average electrical conversion efficiency of the generator working at partial load are quite above the initial baseline. Therefore the scope of improvement is importantly limited.

When benchmarked the hybrid PTO with the fully electrical counterpart it is obtained a 10% improvement on the mean annual electrical power and a 296% increase on the capacity factor. The progress on performance is still modest but encouraging. In fact case study results are limited by the Wells turbine which is unable to harness the most energetic peaks of power. In fact, simulation results for the OWC family (not considering air turbine efficiency) show that generator efficiency can be increased up to 32%. Therefore, performance improvements for OWC devices can be expected in the range of 10-32%.

Other device families can also benefit from the novel PTO. The best in class is OWC, followed by attenuators, point absorbers and OWSCs. According to simulation results, the submerged pressure differential family only gets a marginal improvement.

Locations with moderate energy and high variability (e.g. EMEC and BiMEP) can improve their electrical conversion efficiency by 11-32% thanks to the use of the hybrid PTO. The scope of improvement is reduced to 3-8% for locations with moderate variability and high energy such as Belmullet.

Survivability

The hybrid PTO makes the generator work in a safer regime and allows using smaller generators for the same WEC device.

Torque variability in the baseline configuration (fully electrical PTO) was slightly greater than originally estimated but the hybrid PTO is able to reduce this fluctuation to 5 times in the generator (3-fold improvement**).** The progress in this indicator is greater than anticipated. Besides, simulation results for the OWC family (not considering air turbine efficiency) show that survivability can be reduced up to a 6-fold factor.

All device families can meet or exceed the survivability target by using the hybrid PTO. Submerged pressure differential is best in class, followed by OWC, point absorbers, attenuators and OWSC.

Availability and affordability

The single failure mode considered in this feasibility study was the thermal fatigue of the electrical generator.

Even though the cyclic fluctuations of torque above the nominal power were expected to contribute to this failure mode, the insulation temperature is not significantly increased for the optimum generators. In both cases the expected life is well beyond the project lifetime.

Device unavailability and operating costs are a consequence of reliability and site accessibility. As the expected life in both cases is well beyond the project lifetime, these metrics do not show any improvement, since results are just dependent on the preventive maintenance strategy and different site accessibility.

LCOE

As simulation results indicate that the generator life will be greater than the project lifetime of 20 years, the long term reduction of the LCOE for the case study is only dependent on the PTO CAPEX and the energy production.

Lack of information on the cost of hydraulic components does not allow a definite conclusion on the final CAPEX of the hybrid PTO. However, as the share of the PTO costs in the farm CAPEX is just a small fraction, it can be anticipated that a great part of the energy production can be transferred into LCOE reduction.

This means for the OWC type of device that a 10% improvement in energy production can be translated into a 6% reduction of LCOE even if the hybrid PTO CAPEX were increased to 150% the baseline cost of the fully electric PTO. Similarly, a 32% improvement in energy production can be translated into a 22% reduction of LCOE. Therefore, the hybrid PTO can be expected to impact the long term reduction potential on LCOE in the range of 6-22%.

1.7 Communications and Publicity Activity

In accordance with the agreement, WES must be notified prior to any press announcement or publication of project results. The only communication of this project has been done in the framework of the WES organised workshops:

- Wave Energy Scotland Inception Workshop (17-18th November, 2015): Power Take Off Presentation.
- Wave Energy Scotland NWEC Workshop (18-19th April, 2016): Power Take Off Poster.

1.8 Recommendations for Further Work

Generator efficiency curves have been modelled from manufacturer efficiency data at partial loads. However, low generator efficiency at low power loads, which are high probable within each sea state, seem not to be reflected in the final average conversion efficiency. In fact, results seem rather optimistic for a wave energy application. As performance is highly dependent on the accurate estimation of individual components' efficiency at partial loads, it is therefore strongly recommended to carefully verify and calibrate generator efficiency curves with laboratory tests in Stage 2 to reduce this uncertainty.

- Collect information directly form component suppliers, European projects, databases and literature.
- Calibrate official catalogue information with laboratory tests

Control cannot be practically implemented if component actuation timescales do not match the simulation requirements (i.e. large inertia of hydraulic components). It is recommended to:

- Refine control models to realistic represent time response of components and systems.
- Use state-of-the-art integrated components such as the Artemis variable displacement motor/pump.

The single failure mode considered in this feasibility study was the thermal fatigue of the electrical generator. The insulation life reduces rapidly with an increase in temperature. In both configurations the expected life of the PTO is well beyond the project lifetime. Even though the cyclic fluctuations of torque above the nominal power were expected to contribute to this failure mode, the insulation temperature is not significantly increased for the optimum generators. The failure mode selected limits the extent of conclusions drawn regarding availability and affordability. It is thus strongly recommended to:

- Investigate other failure modes of both the electrical and the hydraulic components of the hybrid PTO.
- Perform a formal technology risk assessment of the hybrid PTO to inform the design process.
- Refine techno-economic models with laboratory tests.
- Refine affordability and availability target outcomes.
- Involve a relevant manufacturer of hydraulic systems in order to define quantitative targets for the PTO CAPEX.

The quantification of the PTO operating cost has required the utilisation of a bespoke techno-economic model for the wave energy farm from OCEANTEC. Absolute values of the affordability can be highly dependent on the deployment site, wave farm size and device being considered. An in depth knowledge of the WEC technology and commercial farm is required to produce a realistic estimation of the LCOE. It is therefore strongly recommended to develop a refined techno-economic model in Stage 2 to allow a more equitable comparison of the PTO under different conditions. This techno-economic model will also inform the long term reduction of LCOE due to the hybrid PTO.

- Refine techno-economic models with parametric CAPEX. Select broadband prime movers.
- Establish linkage with technology developers.