EMERGE (Electro-**ME**chanical **R**eciprocating **GE**nerator**) project**

WES PTO Stage 3

Public Report

UMBRAGROUP spa

This project has been supported by Wave Energy Scotland

1. Project Introduction

This document provides a summary of the EMERGE (Electro-MEchanical Reciprocating GEnerator) project, commissioned by Wave Energy Scotland (WES) under a stage 3 contract as part of the call for Wave Energy Converters (WECs) Power Take-Off (PTO) systems.

The project embraced a series of activities to facilitate the technology transfer of a well-proven, highly efficient Electro-Mechanical Actuator (EMA) derived from the aeronautic and industrial sectors, and developing this concept as a generic PTO option for wave energy applications (see Figure 1). The ballscrew generator inverts the basic operation of an EMA and integrates two systems: a reciprocating ballscrew, which converts linear motion into rotary motion, and a permanent magnet generator, which converts rotary motion into electricity.

The project was undertaken by UMBRAGROUP from Italy, world leader in the production of recirculating ballscrews and electromechanical systems for the aeronautical, energy and industrial sectors.

The project has proven the performance and robustness of the ballscrew generator. Indeed, it has been widely assessed in both laboratory and open sea tests, successfully withstanding a large pool of different load conditions.

2. Description of Project Technology

A screw is a load-carrying mechanical component able to convert linear motion into rotary motion and vice versa. This concept is easy to understand if we think of the screws we use at home. A ballscrew, as simply shown in Figure 2, is a mechanical device in which the "balls", acting as low friction load-carriers, convert the linear motion of the "screw" into rotary motion of the "nut". Thanks to the balls, the axial load at the screw is converted into a torque at the nut, which is free to rotate about the axis of the screw but axially constrained. The rotational speed of the nut is a function of the screw linear speed and the screw pitch (i.e. the axial distance between adjacent threads on the screw).

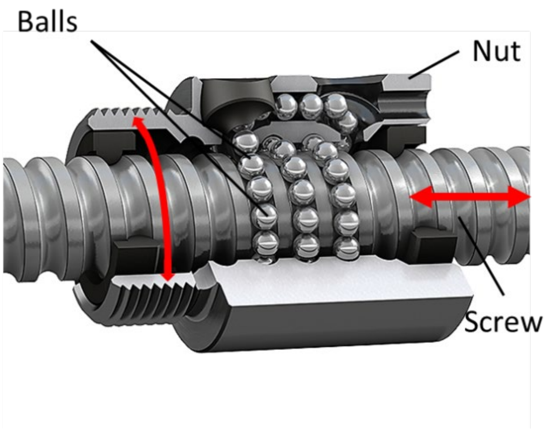


Figure 1 Schematic representation of a ballscrew system

Permanent magnets are integrated in the nut, which acts thus as rotor of the electrical generator. The rotor spinning inside a specially designed stator produces electrical output energy through electromagnetic induction. The frequency of the induced voltage and current on the stator windings is proportional to the input speed and generator number of poles. The screw pitch and number of the generator poles are thus adjustable parameters that can be tuned to match the requirements of a specific application.

UMBRAGROUP’s ballscrew technology has been successfully adopted in various sectors including aerospace, industrial, military, nuclear and medical. Compared to the presently most popular PTO choices for wave energy (namely hydraulic, other direct drive and pneumatic), this system has several clear advantages including:

- Efficiency: mechanical power is directly converted into electrical power, without the need of an intermediate conversion step. Mechanical efficiency is high due to the small friction within the system (only rolling contact elements are used). Rotary motion amplifies the magnetic fields variation, leading to a higher electrical efficiency.
- Reliability: the short energy conversion chain and the reduced number of components increase system overall reliability, minimizing mean time between failures (MTBF) and downtime for maintenance and parts replacements.
- Survivability: the ballscrew technology is able to withstand high fatigue cyclic loading. The high efficiency delivered for a wide range of loads allows the generator to perform well in high load ratios or low capacity factors situations.
- Applicability: thanks to the linear reciprocating motion between input shaft and housing, the application of a ballscrew generator to WEC types such as point absorbers and submerged pressure differential is straightforward. An easy adaption of the ballscrew generator to WECs where a rotating motion occurs (such as oscillating wave surge converters and attenuators) can be implemented by placing the generator inside a pin-to-pin connection between the moving parts.
- Costs: the overall short energy conversion chain (with consequent reduction of the number of components used) and the use of few costly active materials for the electric generator (such as magnets, copper and ferromagnetic) result in competitive costs for the PTO.
- Manufacturability: the system has a relatively simple architecture, with a reduced number of components. The derivation from an already industrialized device allows for a lean and optimized production cycle, that is already available. Production and assembly costs are consequently within competitive known boundaries.
- Power density: all the components needed for mechanical to electrical energy conversion are integrated inside a compact envelope, with a relatively small weight. This reduces the impact of PTO installation on a WEC both in terms of time and space requirements.

3. Scope of Work

The work undertaken in this project consisted in a detailed characterization of generator performances under different operating conditions. In particular, the following activities took place:

- In-house tests to asses generator functionality
- Bench tests at an external laboratory to asses generator performance under different damping factor setups and input conditions
- Submerged test to asses generator sealing capabilities both in static and operational mode
- Sea trials at Scapa Flow (Orkney – Scotland) to assess generator performance under open sea conditions

During the in-house tests, the ballscrew generator was axially connected to an electro-mechanical actuator (EMA). The EMA was controlled so that a specific axial position profile (trapezoidal, sinusoidal or irregular) could be imposed to the ballscrew generator input shaft, which was connected to an electrical load in order to simulate the power production. The test campaign continued in an external laboratory for the full characterization of the EMG.

Figure 2 and Figure 3 show architecture and the layout of the test bench setup used in this phase. The aim of this activity was to assess generator performance for a wide range of operating conditions in terms of screw axial speed and electrical damping factor, as well as assessing EMG durability though High load accelerated endurance tests.

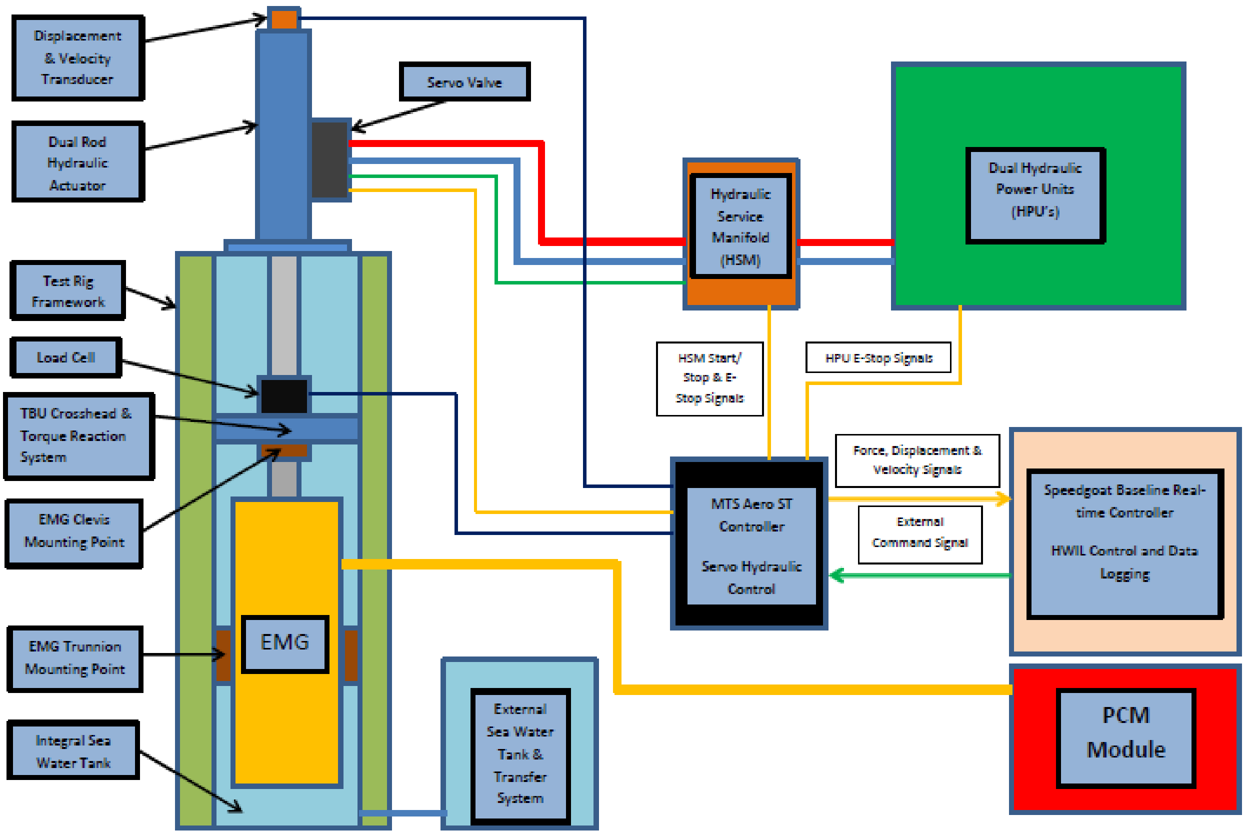


Figure 2 Diagram of H-TBU architecture.

In this case the load was applied from a hydraulic unit, which facilitated a comparison of the different technologies and also gave an idea of the differences in size and envelope. Figure 4 gives a comparison at glance of the generation and actuation system.

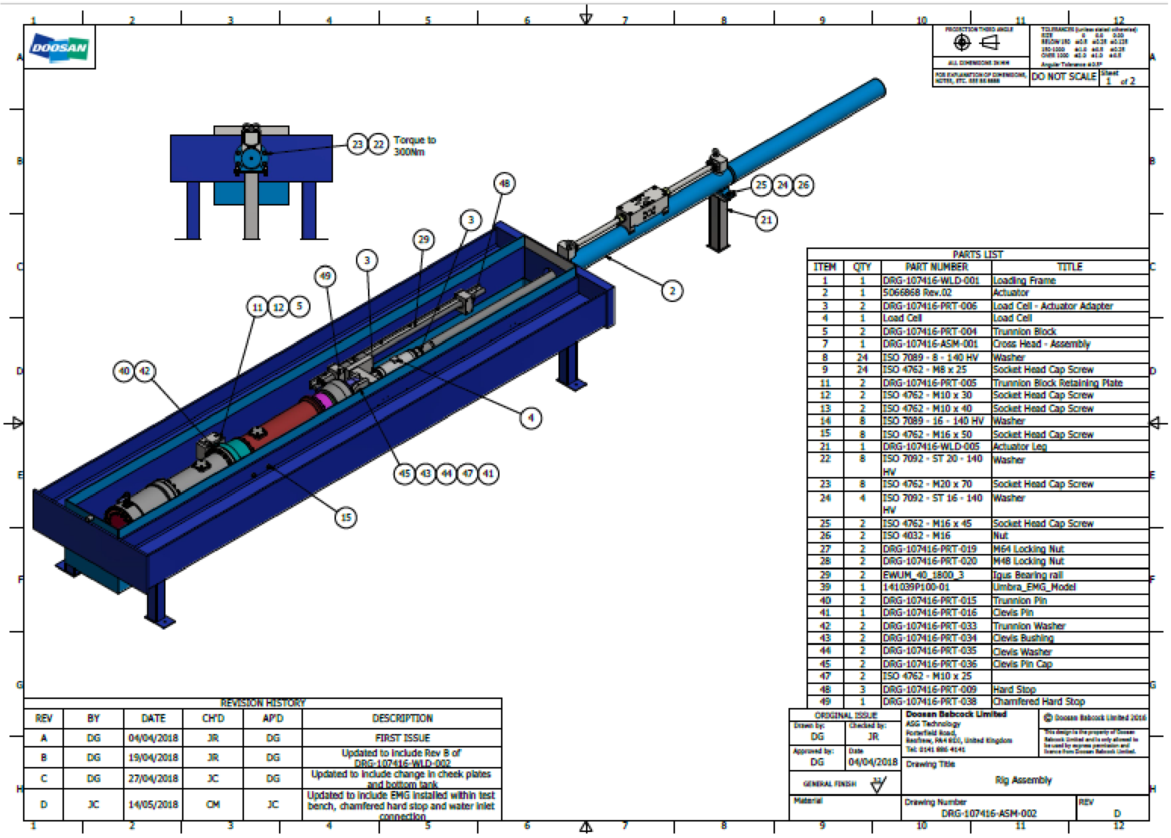


Figure 3 Drawing showing overview of Test Bench.

Figure 4 Overview of Test Area showing both H-TBU and Test Bench.

At the end of the test campaign sea trials have been performed, where the generator was connected to a point-pivoted buoy and installed onto a barge moored in an open sea spot in Scapa Flow (Orkney islands). The buoy shape is similar to that used in stage 2, but with some upgrades to make it even more hydrodynamically efficient. The generator was placed between the buoy and a support structure, the connections were performed through two mechanical hinges (see Figure 5).

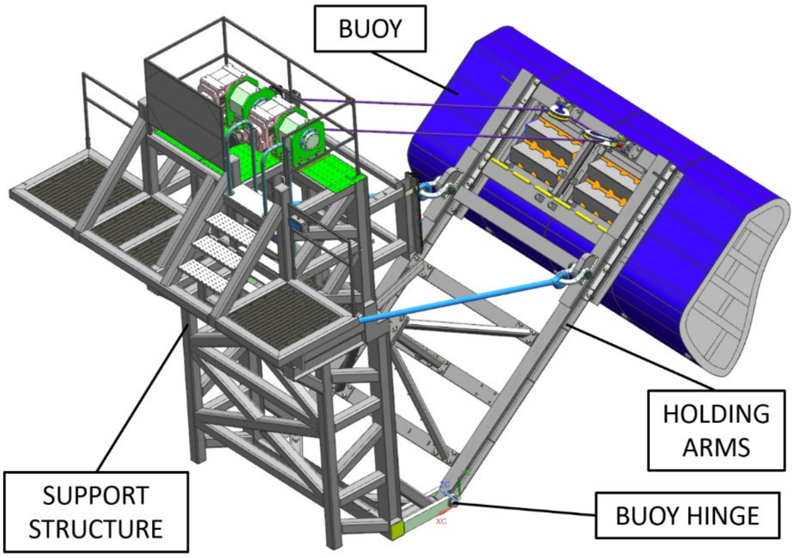


Figure 5: Indicative view of sea trials WEC configuration.

The system was deployed in the sea water for 14 weeks and it successfully withstood 8 weeks of open sea tests. Protection systems have also been largely assessed, confirming safety procedure effectiveness.

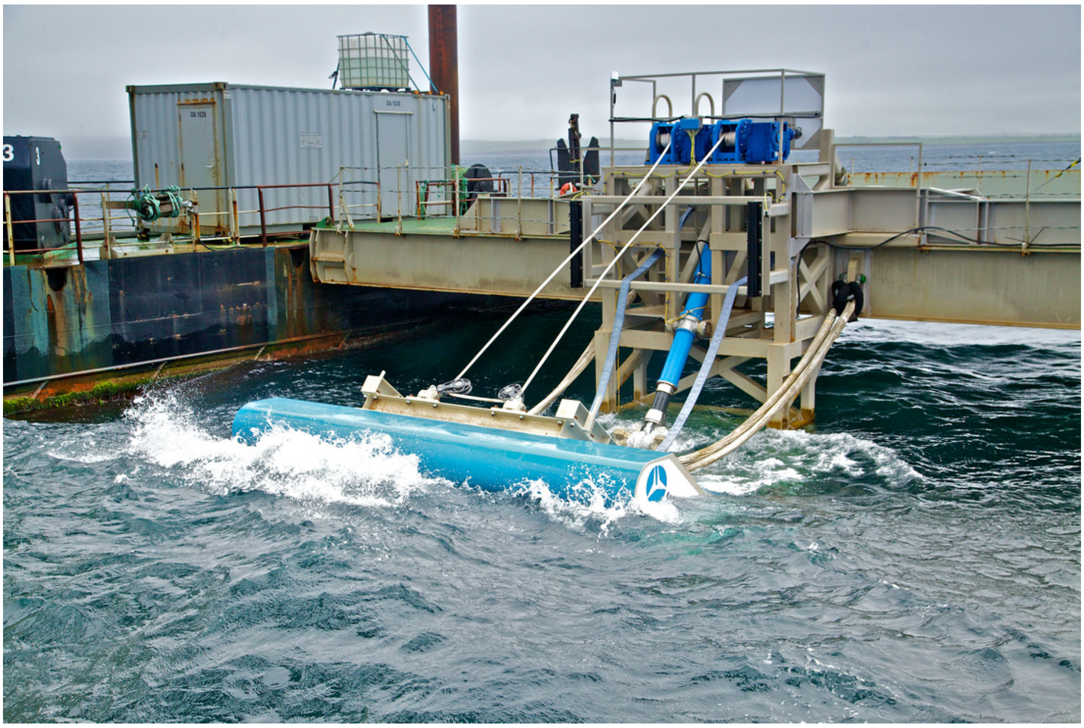


Figure 6: WEC operating during sea trials in Scapa Flow

4. Project Achievements

The main project goal of TRL 7 (Technology Readiness Level) for the EMG technology has been the achievement throughout the duration of the project. This has been achieved by performing both EMG laboratory bench tests and sea trials. Testing procedures have been inspected and verified by a third party (Bureau Veritas MARINE & OFFSHORE) which has also been provided with data analysis results and issued conformity certificates and technology assessment to ensure successful TRL 7 achievement.

- Bench tests EMG efficiency has a plateau value of 0.7128 (as shown in Figure 6). It is quite stable across the speed>200 mm/s region, as a comparison WES stage 2 showed efficiency values around 0.8

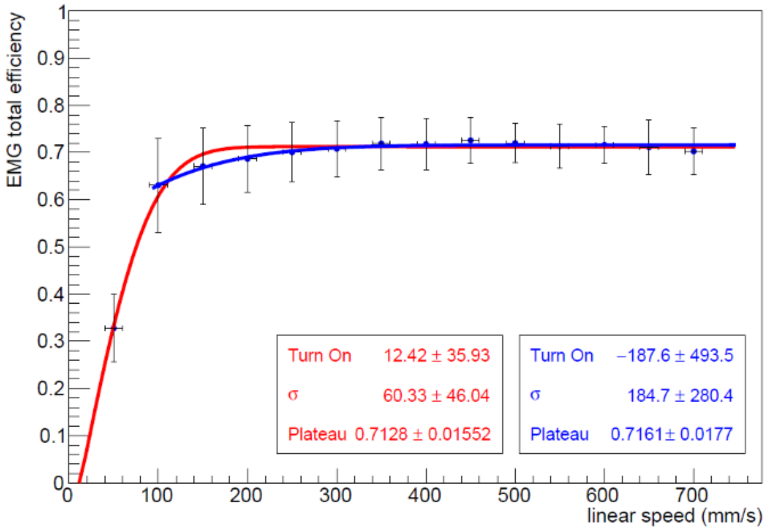


Figure 7 AC electrical efficiency vs speed (bench tests)

- Sea trials efficiency (Figure 7) is near to 0.7 in the optimal working region, a quite encouraging result, aiming probably to an even more energetic sea deployment site. It is quite variable across the system working speeds and most of the bench test optimal speed points (>200 mm/s) are missing. For this reason and considering project sustainability, a more energetic deployment site is foreseen for future project development, with the aim to access higher EMG load conditions. Bench tests efficiency plateau value is confirmed.

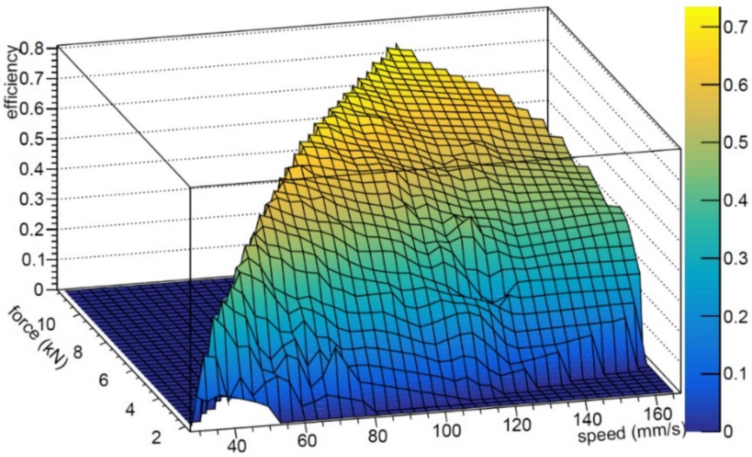


Figure 8 AC electrical efficiency vs force vs speed (sea trials)

5. Applicability to WEC Device Types

EMG is applicable to several WEC types. EMG has the potential for representing an important step-change in the wave energy sector, in terms of both performance and reliability. It aims at replacing hydraulic, pneumatic and linear electrical PTOs for any application that requires conversion of linear motion into electricity. In wave energy, examples of this include point absorbers, submerged pressure differential, attenuators and oscillating wave surge converters, which represent 82% of the installed WECs (D. Magagna and A. Uihlein, "JRC Ocean energy status report," European Commission, 2014).

A wide range of different devices can easily accommodate the EMG if properly tailored or, vice versa, it is possible to redesign the device around available EMG sizes. The following table provides an overview of the most common WEC types and describes the compatibility of EMERGE EMG with such.

Device Family	**Applicability (Y/N)**	**Comments**
Attenuator	Y	Applicability is straightforward, with EMG connecting adjacent structural components of the attenuator in a pin-to-pin configuration. Engineering solution already demonstrated by UMBRA in laboratory tests on undulating carpets for tidal energy conversion. Possible customers or development partners: AlbaTERN Ltd, Crestwing Aps, Grey Island Energy Inc., Mocean Ltd.
Point Absorber	Y	Applicability is straightforward, with EMG damping the linear, heaving relative motion between the two bodies forming the point absorber. Advised connection is pin-to-pin. Possible customers or development partners: Ocean Power Technologies Inc., Seabased AB, Wedge Global, Corpower.
Oscillating Wave Surge Converter	Y	Applicability is possible, introducing a lever mechanism that converts the rotational motion at the hinge into linear motion. Possible customers or development partners: AW-Energy, BioPower Systems Ltd.
Oscillating Water Column (OWC)	N	EMG is not applicable.
Overtopping/Terminator	N	EMG is not applicable.
Submerged Pressure Differential	Y	Applicability is straightforward, engineering solution similar to that for point absorbers. Possible customers or development partners: Carnegie Clean Energy Ltd., Calwave Inc.
Bulge Wave	N	EMG is not applicable.
Rotating Mass	N	EMG is not applicable.
Other	Y	Point-pivoted buoys (such as that used in this project). Possible customers or development partners: Eco Wave Power.

Table 1 Overview of the WEC families and EMG applicability

Among these some architectures have been identified as more promising and with the strongest potential for EMG technology. In particular WEC architecture compatible with EMG design are described and represented in Table 2.

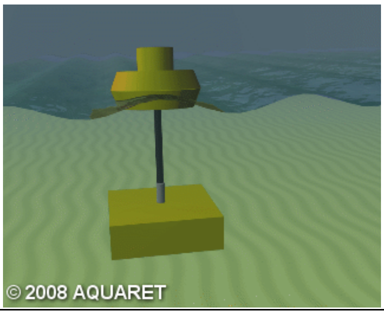
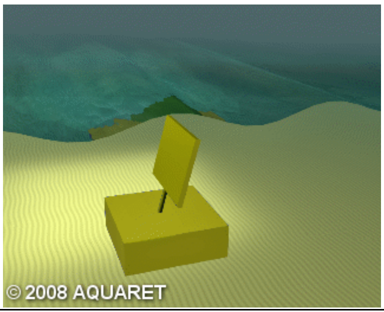
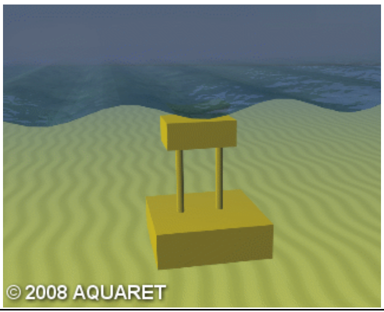
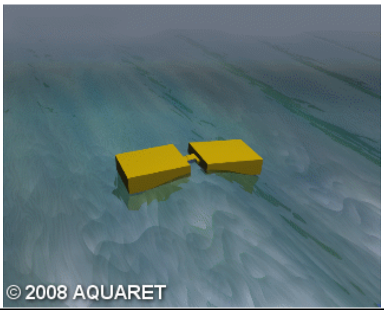
Point absorber Floating structure which absorbs energy from all directions through its movements at/near the water surface. It converts buoyant top motion relative to the base into electrical power. Power take-off system depending on displacers/reactors configuration.	
Oscillating Wave surge converter Extracts energy from wave surges and from movement of water particles within them. Arm oscillates as a pendulum mounted on a pivoted joint in response to water motion.	
Attenuator Floating device which operates parallel to wave direction and effectively rides the waves. This kind of device captures energy from relative motion of the two arms as waves pass through them.	
Pressure differential Typically located near shore and attached to seabed. Wave motion causes sea level to rise and fall above the device, inducing a device pressure differential. Alternating pressure pumps fluid through a system to generate electricity.	

Table 2 Description of WEC architectures compatible with EMG design

6. *Summary of Performance against Target Outcome Metrics*

The following table is a compliance matrix of the target outcomes, with a brief overview on whether grant agreement target outcomes have been achieved or not:

Metric		Description of TO expected (qualitative)	Description of TO expected (quantitative)	Industrial TO expected (quantitative)	Project TO	Industrial TO
Affordability	CAPEX	During the implementation of WP07 and WP08, the EMG will work in relevant and operational environments, respectively. Inspection of the generator after the tests will ensure no damages occurred on any component.	Considering this context (FOAK device), the project CAPEX is in the range 800-1000£/kW of peak electrical power (IEC 60034-1 S6 duty 15%).	Cost of PTO 650£/kW for a 100kW (peak electrical, IEC 60034-1 S6 duty 15%) power generator.	Confirmed	Confirmed
	OPEX	The maintenance targets are mainly related to the PTO itself and only partially deal with the working conditions of a specific application.	OPEX (PTO only) £500/yr.	OPEX is expected to reach values as low as 400-450£/year per EMG by slightly reducing the maintenance frequency based on a maintenance contract agreement.	Confirmed	Confirmed
Performance	Rated Capacity	-	PTO developed in this project will have a 100kW peak electrical power size (IEC 60034-1 S6 duty 15%).	-	Confirmed	-

	Power conversion	-	The efficiency target is to have an average conversion efficiency between 65% and 80%. Efficiency in the axial speed range 0.1m/s - 0.5m/s is expected to be stable (3% deviation from mean value).	The power conversion efficiency for an industrialized PTO is expected to be in the range of 70%-80%.	Partially confirmed	Confirmed
Availability	Reliability	Within the Stage 2 project, the reliability was already assessed by tests, and calculations of FMEA and MTBF.	Confirm the maintainability capabilities of the generator by achieving zero failures indications after the tests in relevant and operational environments.	Expected life of 20 years (continuous operation).	Confirmed	Confirmed
	Maintainability	Failure Modes results are intended to be confirmed and in addition a FMECA study will be provided.	Zero failures.	Maintenance intervals every 4 years	Confirmed	Confirmed
Survivability	Load ratio	The EMG is declared to survive load ratios up to 5.	The EMG is declared to survive load ratios up to 5.	The EMG is declared to survive load ratios up to 10.	Confirmed	Confirmed
	Fatigue loading	The EMG is declared to survive load ratio, while being not affected by fatigue issues for the total period of testing.	No fatigue issues.	-	Confirmed	Confirmed

	Corrosion	EMG will have an appropriate protection (painting or coating) against marine environment (anti-corrosion, anti-fouling).	Marine protection solution is expected to survive without problems for the whole period of testing.	Marine protection solution will be most likely aligned with market standards.	Confirmed	Confirmed
Other	Manufacturability	The Stage 3 prototype is expected to be entirely manufactured in Umbra plant in Foligno using existing equipment, tools and processes. No other novel equipment tools or processes were required.	Production lead time will be 6 months.	Production lead time will be 4 months.	Confirmed	Confirmed
	Installability	Installation of the EMG on the WEC with a pin-to-pin connection performed through simple operations.	Installation time: 8 hours.	Installation procedure will not require extensive equipment.	Confirmed	Confirmed
	Integrability	The Integration of the device is extremely easy and possible in a wider range of systems.	2 mechanical interfaces (hinges) and 2 electrical connectors.	Pin-to-pin architecture of the EMG	Confirmed	Confirmed
	Scalability	The generator is easily scalable up to 300kW of peak power, with the possibility of parallel arrangement or arrays.	Two or three device cases will be evaluated during the execution of this project.	A feasibility study for at least two full scale WECs will be provided.	Confirmed	Confirmed

	Controllability	Demonstrate that the EMG easily works with variable damping	Test at least 3 damping factors	Commercial product will be controllable with a complete range of damping values reacting immediately to input and informing the same system on its status. Ability to be controlled can maximize the efficiency with respect to the working conditions.	Confirmed	Confirmed

7. Communications and Publicity Activity

A number of activities were carried out to promote the project and the outputs:

Conferences and Papers

At European Wave and Tidal Energy Conference 2019 (EWTEC)

- Progress update on the development and testing of an advanced power take-off for marine energy applications
- Numerical and experimental test on a large-scale model of a pivoting wave energy conversion system

At All-Energy exhibition and conference 2019

- Development and testing of an advanced ballscrew-based Power Take-Off for marine energy applications

At Asian Wave and Tidal Energy Conference (AWTEC), 2018

- Design of a 100kW pilot wave energy system based on a ballscrew electro-mechanical generator (EMG)

At European Wave and Tidal Energy Conference 2017 (EWTEC)

- Development and Testing of a Ballscrew Electro-Mechanical Generator (EMG) for Wave Energy Conversion

At 6th International Conference on Clean Electrical Power (ICCEP)

- Experimental tests on a wave-to-wire pivoted system for wave energy exploitation

Oral presentations with accompanying posters were presented yearly at Wave Energy Scotland Conference.

In the ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) journal

- Ocean Energy exploitation in Italy: ongoing R&D activities

Media and Press Releases

Several posts were published on LinkedIN or Facebook Company pages and a promotional video was created showcasing sea tests and activities around the project.

8. Recommendations for Further Work

The analysis in the commercialisation roadmap, delivered in the project, has confirmed that the wave energy market is a sizeable market for UMBRA and one that UMBRA is well positioned for growth in using their robust EMG technology and underlying strong technical and commercial position. UMBRA is also one of the few companies with a strong manufacturing pedigree who are taking an active position in research, development and demonstration of an advanced PTO for marine energy.

The “EMERGE” project has delivered excellent results with a challenging approach never seen before and the ballscrew generator has reached a TRL 7. The next stage of testing to capitalise on project success and explore further opportunities for development is integrating a unit in a WEC and testing in a real sea environment to begin to gather data for a commercial scale unit.

Specific activities in the short/mid-term include:

Technology

User requirements	Continue to research the PTO market to fully understand user needs for the EMG technology. This user requirement study could start with the five WEC developers who sit on the Technical Advisory Board for the H2020 IMAGINE project that UMBRA is leading.
Technology Development	Continue to develop and prove the EMG technology in the wave energy sector.
	Develop the EMG based on robust WEC requirements to be 'WEC ready'.
Competitor Analysis	Continue to monitor the activities of competitors to identify opportunities for collaboration on the supply of components or sharing of methods/lesson learnt. There may also be opportunities to step into projects when other PTO suppliers cannot proceed.

Route to Market

Test and deployment opportunity identification	Understand the up-to-date situation regarding global wave energy opportunities, the policy initiatives and market incetives available.
	Identify WEC or TEC developers actively trying to enter the off-grid markets. Being involved with their projects can provide early market opportunities that are not reliant upon government policy for marine renewables.
	UMBRA should assess other sectors (non-marine energy) where opportunities may exist for the EMG.
Market requirements	Understand rules and eligibility regarding potential opportunities.
	Assess prospects for project development.
Promotion	External - Strong industry and research community event presence is required to increase awareness and build relationships with potential funders, partners and users.
	Internal - The market growth forecasts should be used to support the business case and strategic decision making within UMBRA as they indicate a significant potential long-term market. The forecasts should be refined over time as greater confidence is built around the underpinning growth assumptions.
Targetting demonstration opportunities	There is a need for demonstrator projects in some of the key markets. Identify key opportunites in the target areas and progress these.
	UMBRA should seek to develop further demonstration opportunities with actual partners and identify any other wave/tidal developers who may have requirements for a linear PTO.

Infrastructure

Manufacturing capability	Continue to invest in their manufacturing processes that can in turn offer further cost reduction and performance improvements for the EMG production.
Supply Chain Development	Continue to work with supply chain partners to optimise the solution for marine energy applications, in particular with suppliers of power control equipment. This could also benefit from input from experts in research and academia.
Testing facilities	Promote the development of an in house linear test rig facility or a public lab facility, possibly driven by a ball-screw actuator. This could serve UMBRA and the sector.

Environment, Regulation and Legislation

Noise emissions	In demonstration projects noise monitoring of the EMG should be undertaken under different operating conditions and environments to assess the impact.
Corrosion Protection	Work closely with environmental experts to understand any restrictions on lubricants, paints or other material ordinarily used to improve the compatibility in the marine environment. If required, suitable alternatives can then be identified and put under test to confirm compliant alternatives.
Health and Safety Standards and procedures	Experience and lessons learnt from demonstration projects should be shared for the benefit of the sector.
	Contribute towards efforts to establish best practise guidance and standards and use its position as an experienced aerospace supplier to drive up standards.
Certification	Support the development of IEC standards and their adoption by the industry.

The remarkable experience gathered in the commissioning and decommissioning of the sea trials and in general in the whole project can be used to reduce risks and faults in similar activities.

9. Useful References and Additional Data

For any request or information related to the project itself or to the EMG technology please refer to:

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