Modular electrical generator power take off system for wave - MEGA WAVE PTO

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Abstract - **A wave energy device operates in a wide range of sea states from low load to 4 to 8 times rated load over a wide speed range. Existing PTOs combine mechanical speed enhancers with conventional high speed electrical generator and power converter, with questions over reliability and cannot operate over wide operating ranges. The EU funded MEGA WAVE PTO project is addressing this challenge by developing an all-electric power take off incorporating three sub-systems: a contactless magnetic gear; the modular C-GEN generator; and modular power electronics. The rationale for the technology choice for the all-electric power take off is summarised to provide context. An outline of the methodology is presented through six main themes ranging from engineering design, control and testing, to levelized cost, carbon footprint and supply chain analysis, all with the main aim to demonstrate a scalable, reliable and maintainable fully integrated all-electric modular PTO system customized for wave energy devices from kWs to MWs across the Blue Economy sector. Preliminary work from two deliverables completed in the first year are presented to show the design of a 1000 Nm magnetic gear prototype, and a framework for life-cycle assessment of wave devices to understand the potential impact of MEGA WAVE PTO on carbon footprint.**

Keywords—**Electrical Generators, Magnetic Gear, Modular Power Electronics, Wave Energy.**

I. Introduction

The MEGA WAVE PTO project will develop a fully modular all-electric power take off (PTO) optimised for all aspects of wave energy operations including transport, installation, operability, availability, maintainability and survivability. A wave energy device operates in a wide range of sea states from low load to 4-8 times rated load, but there is no single wave PTO that satisfies such a demanding load regime. MEGA WAVE PTO addresses this issue through modularity in all aspects of the power train – the magnetic gear, the generator and the power electronics. Benefits of modularity have been demonstrated in sea trials in the Mocean Blue-X device which utilises a modular CGEN generator, the core technology of MEGA WAVE PTO. Blue-X is able to operate at 5 times rated speed by re-configuring CGEN modules during operation to match the generator output to the device speed, thus protecting the power converter from overvoltage, and increasing energy output and availability. The ability to switch out modules enables fault tolerant operation, so that power can be generated during fault conditions. O&M operations are reduced as only the faulty module needs replacing, which can be achieved in-situ. All electric modular MEGA WAVE PTO can potentially reduce LCOE by 30-40%, increase availability by 50% and reduce OPEX by 50%, compared to existing PTOs.

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The market opportunities of Wave Energy Converters (WECs) can be divided into three sector scales, utility (1MW +), Subsea asset power (100s kW) and off-grid systems for aquaculture, marine observation (<10 kW). According to ETIP Ocean if Europe leads the global market in ocean energy it will result in €140bn of economic activity, and create 500,000 jobs by 2050, providing significant opportunities for the EU supply chain [1]. The IPCC estimate the annual global wave energy production to be 29,500 TWh, almost 10 times the EU annual electricity demand [2]. To achieve cost effective commercial WEC operation within each sector, an ideal PTO must react large forces or torques whilst operating at low velocity; convert variable voltage and frequency to appropriate power signals; while exhibiting high reliability, availability and efficiency over a wide range of loads. All aspects of this demanding specification contribute directly to the LCoE, and hence economic feasibility, of the majority of devices in all sectors. Fig. 1 shows the primary PTO options used in wave energy devices. Typically, such PTO options consist of three components: a mechanical speed enhancer or storage system, combined with an off-the-shelf high-speed electrical generator, connected to the grid via a power electronic converter. Hydraulic systems offer high force density at low speeds and built-in energy storage driving a conventional off the shelf electrical generator at fixed speed, as installed within Pelamis, Wave Star, Oyster, and WaveRoller. While initially promising, the complexities of using hydraulics as a speed enhancer, became apparent when Aquamarine suffered multiple component failures in 2014 in pistons, accumulators, valves and hoses. The Aquamarine example demonstrates the challenges of using components not designed specifically for wave energy. Efficiency of a hydraulic PTO is dependent upon pressure and flow rate with values quoted as high as 90%, but also as low as 40% depending upon operating conditions. Pelamis suffered from limited piston displacement, limiting operational conditions at sea. Given the pitfalls of hydraulics, developers have gravitated towards more direct mechanical drive systems. Corpower's innovative linear-to-rotary mechanical gearbox leverages high-speed machines typically used in the automotive sector. Mocean Energy's Blue-X device incorporates a mechanical gearbox coupled with the bespoke modular CGEN generator. Similarly, Umbra employs a mechanical ball screw system to translate linear motion into rotary action. Yet, the overarching challenge for these mechanical systems remains reliability and the ability to operate over a wide speed range. Experience in wind energy has shown that gearbox failures cause long downtimes, reducing availability, with an average replacement cost of €230,000 [10]. The wave energy sector would likely experience similar challenges; a failure in the mechanical interface necessitates the complete removal of the PTO, leading to prolonged downtimes. In contrast, direct drive systems, which exclude the gearbox, hint at enhanced reliability. Since 2004 only a handful of direct drive WECs have been reported; SEABASED, Archimedes Wave Swing, and Colombia Power Technologies. Keysan et al highlighted the challenges of direct drive WECs, namely the very low speed, typically equivalent to 1 rpm, leading to an uneconomic solution. Dielectric Elastomers based PTOs offer a non-electromechanical solution. Although tank scale models rated at a few Watts have proved the concept, more work is required scaling up to kW levels in terms of materials and power conversion. Inertia PTOs adopted by Wello and ISWEC involve an oscillating mass or gyroscopes coupled to a conventional low speed permanent magnet generator (PMG). Any fault in the PMG will require complete removal of the machine resulting in costly long downtimes.

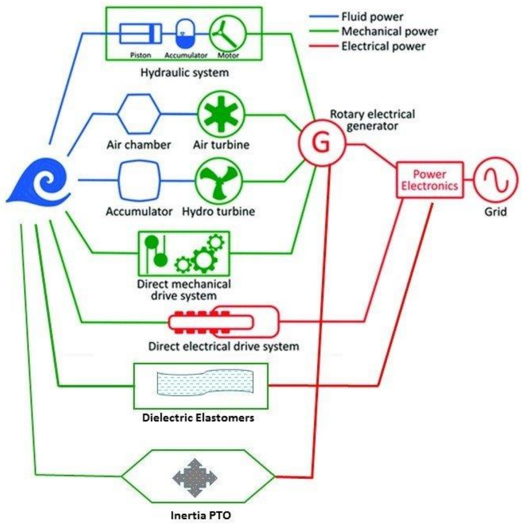

Fig. 1. Classification of Wave Power Take Off.

Therefore, there remains a pressing need for a PTO technology to be developed that can meet the unique demands of wave energy at any scale. In this project, we will demonstrate how the MEGA WAVE PTO integrated system can address the varied challenges and produce a scale-able, reliable, adaptable, and therefore, affordable electrical power conversion solution. The MEGA WAVE PTO system is an all-electric power take off system linking the wave device to the final load. In terms of classification, it is a pseudo direct electrical drive system incorporating three sub-systems all with a high degree of modularity: a magnetic gear as the speed enhancer; the C-GEN permanent magnet generator; and adaptive power electronics. With respect to Fig. 1 it fits between direct mechanical drive and direct electrical drive.

II. MEGA WAVE PTO TECHNOLOGY

MEGA WAVE PTO Concept is a fully electro-magnetic drivetrain to convert low speed high torque from a wave device to deliver consistent electrical power outputs. The system combines the proven C-GEN generator concept, with the efficiency and survivability of magnetic gears and modular power electronic converters resulting in a pioneering all-electric drivetrain. The design philosophy for MEGA WAVE PTO is to holistically integrate the three sub-systems to develop a single electrical generation system package with control and condition monitoring designed to cater for the wave energy sector. This stands in contrast to alternative PTOs for wave energy, which often rely on a more disjointed assemblage of off-the-shelf components, leading to suboptimal powertrain efficiency, reliability and value.

A. Cascaded Axial Flux Magnetic Gear

The Cyclone concept: this replaces conventional contact gearing methods converting low speed high torque to higher speed lower torque more suitable for optimal generator design. In a magnetic gear, torque and speed are transformed through the interaction of magnetic fields with no physical contact, rather than the engagement of mechanical cogs or the use of hydraulic components. Notably, during periods of extreme wave conditions, these magnetic gears offer the unique advantage of temporary disengagement, thereby significantly enhancing system survivability. Once extreme conditions subside, the gear re-engages, ensuring minimal system interruption and impact. The inherent wear-resistant nature of this non-mechanical system accentuates both its reliability and availability. Its axial design provides seamless integration with the axial C-GEN generator.

B. C-GEN Axial Flux Modular Generator

The unique aspect of C-GEN lies in its modularity which is illustrated in Fig. 3. Air-cored stator coils, set in non-magnetic materials like epoxy, can be easily inserted or removed from the Permanent Magnet (PM) rotor, eliminating highly damaging magnetic attraction forces and cogging. The exploitation of this machine topology allows the production of modular, stackable units, suitable to batch process in assembly line manufacturing. These modules are highly transportable, fitting within standard shipping containers and allowing for efficient on-site assembly.

Moreover, its design facilitates fault-tolerant operations, simplifies maintenance, enhances both reliability and availability, and thus reduces system LCOE. The C-GEN axial rotor can also seamlessly integrate into the high-speed stage of the magnetic gear. This synergy allows structural mass and materials to be consolidated, leading to a unified electrical drivetrain.

C. Modular Power Electronics & The Electric Gear Concept

The MEGA WAVE PTO's power converter is a multifaceted system, performing crucial functions such as: (i) Aligning the drivetrain with the wave device to optimise energy capture; (ii) Adapting the generator's variable output for the load; and (iii) Offering resilience

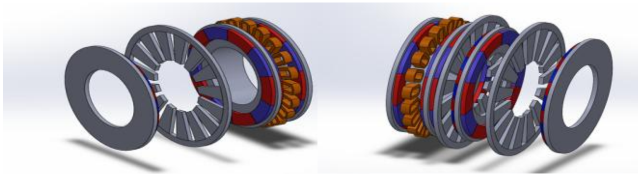

Fig. 2. Left: Axial Single Stage Gear with axial generator; centre: 2-stage axial gear with axial generator; right: torque decoupling in extreme event at 1.8s and 5.8s.

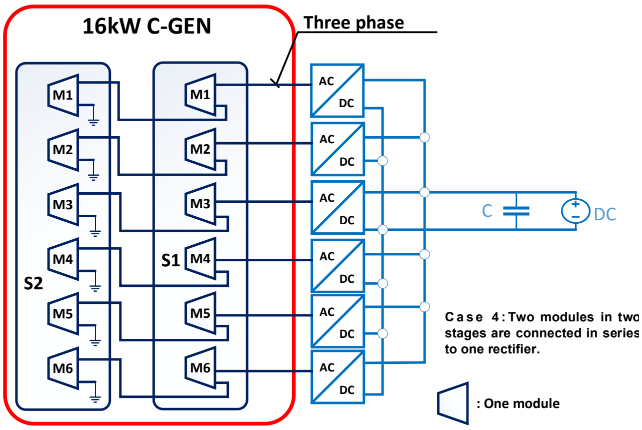

Fig. 4. Six power converter modules per twelve CGEN generator modules [3].

control during extreme wave conditions and internal fault scenarios.

The fluctuating voltage profiles intrinsic to wave devices pose challenges for traditional semiconductor devices. The power converter must deal with a wide range of load and no load voltages at the generator due to the variable speed from the wave device, up to 4-8 times rated operation. By combining the modular aspect of C-GEN with modular power electronic systems and UEDIN's novel electrical gear concept, this challenge can be overcome by actively switching generator coils to regulate voltage output. This not only optimises power conversion but also offers a fault-tolerance mechanism. The modular design of the power converter allows dynamic, in-situ replacements without interrupting generator operations. Fig. 4 shows an example of 6 power converter modules feeding a 12 module CGEN generator. Each power converter module is connected to two series connected CGEN modules in this example. Fig. 4 represents only one example, with others including one power converter module per CGEN module, or 3 power converter modules for 4 CGEN modules, and so on.

III. METHODOLOGY

A. Aim and Objectives

The main aim of the project is to demonstrate a scalable, reliable and maintainable fully integrated all-electric modular PTO system customized for wave energy devices from kWs to MWs across the Blue Economy sector**.** The overall aim is implemented through a number of objectives, listed in Table I.

TABLE I
PROJECT OBJECTIVES

Number	Objective
O1	Demonstrate a fault tolerant all-electrical PTO
O2	Optimise System Performance and Survivability through Control
O3	Increase Reliability and Availability through Condition Monitoring Diagnostics.
O4	Increase availability by 50% & reduce OPEX by 50%.
O5	Use Recyclable Materials for Manufacturing
O6	LCOE reduction of 30 to 40%
O7	Establish an EU Supply Chain.
O8	Engineering & Manufacturing Design Tools
O9	Preliminary Technology Assessment

TABLE II
PROJECT MILESTONES

Milestone	Milestone Name	Due Date
1	Project Governance in place	M6
2	Website	M6
3	1kW system complete	M18
4	1kW Tests complete	M24
5	Supply Chain Roadmap	M24
6	100kW demo built and testing commences	M36
7	Exploitation Plan	M36
8	Circular Economy Roadmap	M42
9	LCOE and LCA Design Case Studies	M48
10	100kW Tests Complete	M48

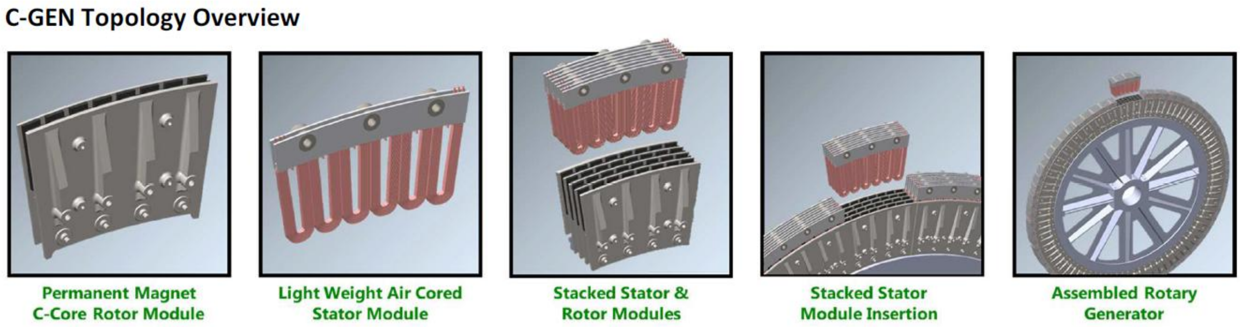

Fig. 3. C-GEN modular concept overview.

B. *Work Programme Themes*

The overall methodology is divided into 6 Work Programme Themes (WPT) linked to individual WPs designed to demonstrate the scalability of the MEGA WAVE PTO across both off-grid and grid connected markets.

1) Lifecycle Engineering Design, Manufacture & Operation
2) Control for Energy Capture and Survivability
3) Experimental Testing & Validation
4) Technology Assessment
5) LCOE & Carbon Footprint Analysis for Device Case Studies
6) Supply Chain Engagement and Analysis

In the off-grid market the scale can be differentiated between low power, supplying instrumentation or aquaculture, less than 5 kW, and supplying offshore assets, in the region of 300 kW. Utility grid systems could be greater than 1MW. We have three wave device partners (Mocean Energy, Sea Potential & CETO Ireland) operating across these scales to provide technical advice and relevant engineering data for design, modelling and testing aspects of the project.

The modular and all electrical drivetrain aspect of the MEGA WAVE PTO technology is an enabling feature that aligns with "do no significant harm" principle as per Article 17 of Regulation (EU) No 2020/852. Modularity reduces wastage of materials, enabling reparability, recyclability and re-use of the components and thus aligning with design for circularity. A team of core partners with expertise in policy, communications, commercialisation, control systems, engineering design & modelling, economics and lifecycle analysis has been assembled to address the themes, with three wave device advisory partners. Industry is included through engagement with the supply chain across different energy and engineering sectors, to inform the team on manufacturability, materials, cost models, lifecycle engineering and reliability data.

To explain the methodology and how it meets the objectives, this section describes the overall MEGA WAVE PTO concept, followed by an outline of the Work Programme Themes, describing the models to be used as well as identifying challenges to be addressed.

A. *WPT1. Lifecycle Engineering Design, Manufacture & Operation*

The holistic design philosophy of the MEGA WAVE PTO provides a step change in PTO technology for wave energy, such that the design and manufacture of the sub-systems are driven by the overall lifecycle requirements including, transportation, installation, maintenance, availability, survivability, and recyclability. Sub-system integration and a high degree of modularity within the MEGA WAVE PTO are key to optimising the lifecycle design. The MEGA WAVE PTO approach differs from existing PTO developers, in which sub-systems are optimised in isolation only in terms of conversion efficiency, and then bolted together without consideration for overall lifecycle performance.

The C-GEN technology with air-cored windings was developed with these criteria in mind, and is an enabling factor in producing a modular generator, which could be easily assembled, maintained, installed and transported. C-GEN has a power conversion efficiency similar to more conventional PM generator technology, but more PM material is required. The additional cost of PM material is offset by other system benefits in assembly, O&M, transport and installation. Lifecycle design involves a compromise between efficiency and overall lifecycle performance. A modular generator enables the use of modular power electronics, which in turn enables more flexible control to tune the PTO to the device characteristics; fault tolerant operation within the generator and power converter; and PTO survivability during extreme events. Fig. 5(a) shows C-GEN modules arranged for transportation, and Fig. 5(b) shows power electronic modules mounted on a C-GEN generator as part of a proof of concept study.

A magnetic gear provides a non-contact speed and torque conversion device, improving reliability compared to a traditional mechanical gearbox. Integration with the generator enables modularity to be extended into the magnetic gear. Fault tolerant control and survivability will be demonstrated through Diagnostic Condition Monitoring techniques, which as far as we are aware has received little attention in the operation of wave PTOs, yet they are essential for lifetime system operation and control, feeding into WPT2, Control and Survivability.

Modularity enables more efficient use of resources by allowing components to be replaced, upgraded, or reused rather than discarded. At larger scales, modular units make recycling and reuse easier to manage, as they can be individually handled, serviced, and recovered, simplifying end-of-life (EoL) treatment and reducing costs and waste. A demagnetised PM rotor module can be replaced and then remagnetised for use in another machine. In the stator, a failed coil blade can be replaced, and the module re-used minimising wastage. The challenge for MEGA WAVE PTO is in the use of recyclable materials, in particular in the stator winding and the rotor permanent magnets. To address this. a supply chain engagement strategy will includes consultation with materials and recycling specialists to better inform the

Fig. 5(a). C-GEN rotor modules for transportation.

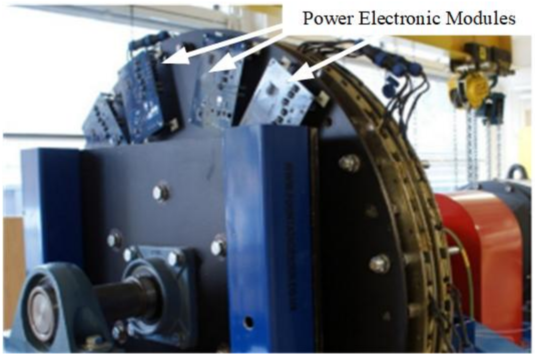

Fig. 5(b). Proof of concept power electronic modules.

engineering design and the impact of more recyclable materials on the lifecycle design. Additionally, this approach will also support identifying manufacturing hotspots where standardised, and energy-efficient production methods can reduce emissions. These experts will engage with the project through the Technical Advisory Board (TAB).

B. WPT2. Control for Energy Capture and Survivability

Wave energy devices operate over a very wide range of load conditions, varying from 4-8 times nominal load. It is uneconomic to overdesign the PTO for such a wide range of loads. The control system links the wave device to the electricity grid or load through the PTO, and has to perform three main functions: (i) Optimal energy conversion control from wave energy to electricity whilst meeting requirements of the load; (ii) Diagnostic control for fault tolerant operation; (iii) Mitigation control in extreme conditions.

Fig. 6 shows the interconnectivity and information flow within the control loops. We will use wave-to-wire system models driven by resource site data to identify loads under different scenarios, and investigate control strategies to reduce the impact of these loads, taking advantage of modularity. Mechanical forces and torques calculated from the device model will feed into a PTO model, from which electrical forces, torques, current and voltage will be determined. In addition, simplified statistical models (developed in WPT1) linking forces, and electrical parameters to component lifetime will be used so that diagnostic and mitigation control strategies can be developed.

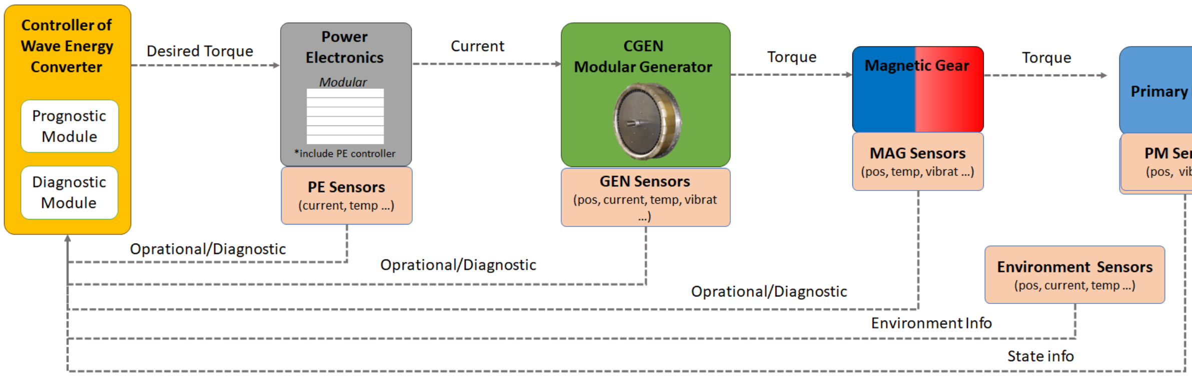

Fig. 6. Control system schematic.

Output from the system modelling, will be used in the lifecycle engineering design tools (WPT1), to better inform component design and enhance reliability. Information on operating scenarios will be provided by our device advisory partners, to ensure that control and engineering design are closely coupled and reflect the real operating conditions and environmental loads. This will be demonstrated in WPT3, Experimental Testing and Validation.

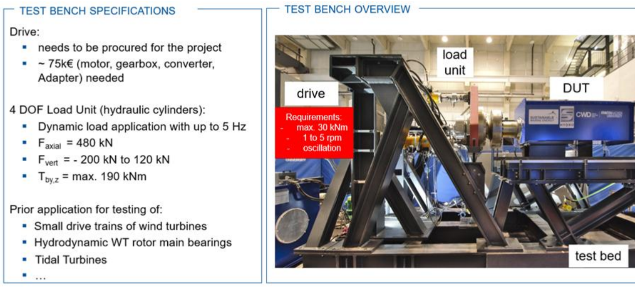

Fig. 7 RWTH test rig.

C. *WPT3. Experimental Testing & Validation*

The development of wave energy technology follows a path involving scale model testing (1/20th to 1/50th scale) in wave tanks in which the PTO is often represented by a simple damper. It is neither economically viable nor technically feasible to test the PTO within a full scale device at sea. The pathway up the TRL curve towards full-scale test must involve prior testing of the PTO in a controlled and relevant environment. Such experimental testing of the PTO in a controlled environment is key in establishing confidence, verifying and validating engineering design tools, learning about control and operation of the system, de-risking, increasing TRL, reducing costs and accelerating time to market. In the test programme we will emulate the operational conditions that would be encountered in a real system, which not only include nominal forces and torques, but also asymmetrical loads, faults and extreme conditions.

The complex hydrodynamic interaction between a wave energy device and ocean waves is challenging to reproduce in a HIL system. The use of nested control systems for different aspects of operation, increases the complexity of HIL implementation. In the MEGA WAVE PTO project we propose a hybrid form of HIL, in which we will use the wave-to-wire system models (WPT2) to define typical operating duty cycles providing a torque-speed demand for programming on the test rig, which will be met by the control system. Extreme events will be included in the duty cycles through the addition of torque and speed perturbations, allowing demonstration of the inner diagnostic and mitigation control loops. The MEGA WAVE PTO test programme is designed to demonstrate scalability, system reliability, optimised performance from nominal to extreme conditions, and thus the system will be tested at two different scales:

(i) 1kW system - Testing at the 1kW level will provide early validation of the integrated system engineering design tools, and manufacturing techniques. It will be tested on an existing test rig at UEDIN which requires minor adaptations. Pure Marine will provide a device structure for testing the 1kW PTO. The test rig will be available for testing other low power devices within the Blue Economy market.

(ii) 100kW system – Increasing the scale to 100kW results in a significant increase in forces, torques etc, verifying scalability and further validation of design tools providing a significant step towards increasing TRL and giving confidence to produce designs for utility scale at MW level. The test facility at RWTH will be adapted to provide reciprocating motion profiles at low speed and high torque, up to 5 rpm and 25 kNm. Asymmetrical loads can be applied to the drivetrain emulating extreme loads transmitted from the wave device to the drivetrain, which will in turn demonstrate electro-mechanical survivability through appropriate diagnostic and mitigation control systems.

D. *WPT4. Technology Assessment*

Independent verification of any new technology gives different stakeholders confidence, as follows: (i) investors and customers gain confidence that the technology will perform according to the design specifications; (ii) technology developers gain confidence in their own design and manufacturing techniques, enabling the production of repeatable designs at different scales; and (iii) supply chain partners gain confidence needed to offer manufacturing services to the technology developer.

MEGA WAVE PTO heralds a new approach to wave energy PTO systems, and thus it is important that technology processes are assessed during design, manufacture and test. In technology assessment the technology lifecycle is divided into manageable elements in order to assess which elements involve aspects of new technology and identify the key challenges and uncertainties. The process will be applied at different stages in the project, so that the output from the assessment can be used to refine the design process. In doing so, the MEGA WAVE PTO will be progressively de-risked within the project itself, therefore increasing confidence in the final product. A TAB consisting of the wave developer advisory partners, DNV and members of the supply chain will provide informal 3rd Party assessment, on for example, material data, manufacturing techniques, wave device characteristics. Consultation with the TAB will ensure that the MEGA WAVE PTO is installable, manufacturable and maintainable taking into account the needs of the wave device developers (representing the customer), and aligned with the capabilities of the supply chain.

E. *WPT5. LCOE and Carbon Footprint Analysis for Device Case Studies*

In order to reduce LCOE it is necessary to optimise annual energy yield, whilst reducing CAPEX & OPEX costs. A high degree of modularity within the PTO provides greater flexibility in influencing LCOE. Due to inherent redundancy, energy can be still be generated even if there is a faulty module, which increases availability and annual energy yield. In a non-modular PTO, the entire system has to be shut down during a fault, incurring downtime and loss of revenue. Likewise, modularity enables in-situ O&M, which has been demonstrated successfully on the C-GEN system currently operating on the Mocean Energy device at Orkney, increasing availability and reducing OPEX. The ability to mass produce large volumes of small modules without expensive tooling and assembly equipment, and which can be transported in standard containers anywhere in the world for final assembly, could result in reduced CAPEX. New LCOE, Life Cycle Assessment (LCA) and O&M models need to be developed in order to fully account for the flexibility enabled by the MEGA WAVE PTO system. Accurate data is required for the LCOE model to be useful and implemented with confidence, but since MEGA WAVE PTO is at a low TRL, this data is not available. We will work closely with the TAB and engage with the supply chain to provide the necessary data. With these

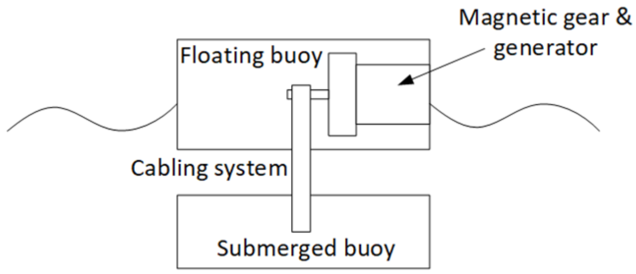

Fig. 8: Sea Potential WEC device.

new models we will work with our wave device partners to perform device design case studies covering off and on grid applications.

The MEGA WAVE PTO design's reduce waste generation and minimise maintenance interventions, supporting lower operational emissions and resource use over time. Furthermore, the improved energy generation from higher system availability contributes to a lower carbon footprint per unit of electricity produced. A focused LCA will quantify the benefits brought by the MEGA WAVE PTO concept, highlighting opportunities to reduce emissions across material choices and EoL strategies.

This integrated analysis will provide results on areas where further cost reductions can be made, and a pathway for LCOE reduction to accelerate the advancement of the MEGA WAVE PTO TRL towards commercialisation as sustainable and scalable solution.

F. *WPT6. Supply Chain Engagement and Analysis*

The design philosophy of the MEGA WAVE PTO is not just about producing the most efficient PTO, it is also influenced by whole system approach that incorporates principles of design for circularity. This includes manufacturability, recyclability, installation, transportation and maintainability. MEGA WAVE PTO is at the concept stage, with each element validated in the lab, and the generator demonstrated in the real environment. The sub-systems within MEGA WAVE PTO have been developed with the lifecycle of the application and market sectors in mind, and hence it does not use off-the-shelf sub-systems. We will work with component suppliers to understand how to manufacture the components so that the sub-systems can be assembled into an integrated product. The manufacture process is also influenced by the use of recyclable materials, ease of transport and installation, and O&M requirements, and thus we require input from relevant parts of the supply chains. As well as informing the design process, this engagement will provide data to better inform LCOE and LCA models. Consultation with the supply chain will not be restricted to companies active in the wave energy sector, and will include aerospace and transport companies, in which reliable and maintainable drivetrains are also a high priority. The potential for knowledge and technology transfer from other sectors is well recognised. Engagement with the supply chain will be facilitated through the Technical Advisory Board, which will meet every 8 months, and workshops covering the different aspects of the supply chain that can influence the design and development of MEGA WAVE PTO, leading to roadmaps providing a clear path towards commercialisation.

IV. Preliminary Results

A number of deliverables have already been completed and submitted, which when published will be available on the project website [14]. A summary of two deliverables will be provided in this section.

A. D2.1 1kW Magnetic gear and generator design

The deliverable is a design study of a small scale PTO for Blue Wave Economy devices such as that developed by Sea Potential. Fig. 8 shows a schematic of the Sea Potential wave device, in which the movement of the floating buoy relative to the submerged flooded buoy causes the cables to wind and unwind, which in turn drives a rotary generator. In this design an axial magnetic gear steps up the speed from 5 to 15 rpm and the generator is a C-GEN permanent magnet generator. A specification of the system was discussed with Sea Potential leading to the following requirements:

- Maximum Outer Radius: $R_{out} = 250\ mm$
- Required Slipping Torque: 1 kNm to 1.2 kNm
- Minimum Gear Ratio: >10
- Operational Speed: 5 to 15 rpm (low speed side)

Fig. 9 shows the main geometrical parameters of the magnetic gear. A sensitivity analysis was undertaken to find the best dimensions to meet the design specifications. In order to meet the target of a gear ratio greater than 10, multiple pole number combinations are possible. The number of poles must be even and it is recommended that the gear ratio is a non-integer, which will reduce cogging torque [15]. Based on the geometrical constraint imposed on the outer diameter, and a previous design of a radial magnetic gear with similar ratio, the number of poles were chosen as follows: high speed pole number, $P_i = 6$; Low speed pole number, $P_o = 62$; and modulator pole number, $Q = 34$. With these pole numbers the gear ratio is:

$$G_r = \frac{\omega_i}{\omega_o} = \frac{P_o}{P_i} = \frac{62}{6} = 10.33$$

Based on the geometrical study the final design is given in Table III:

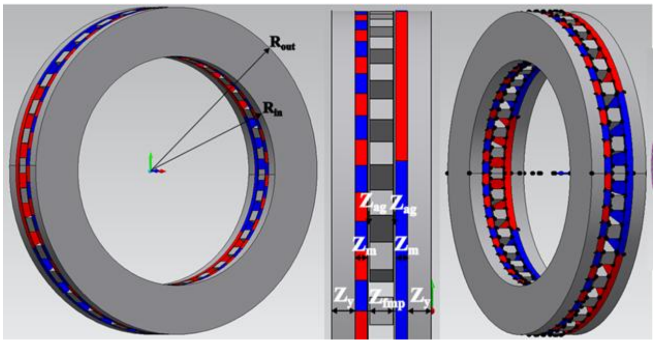

Fig. 9 Dimensions of the magnetic gear: Z_{ag} is the physical airgap between magnet discs and modulator ring; Z_m is the thickness of the magnet on both low and high speed rings; Z_y is the thickness of the rotor back iron discs; R_{out} is the outer radius; and R_{in} is the inner radius; Z_{fmp} is the thickness of the modulator poles.

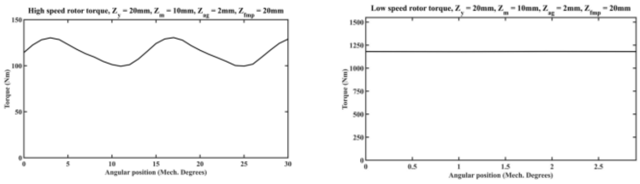

Fig. 10. High speed and Low speed rotor torque with the modulator ring stationary.

Fig. 10 shows the results of torque on the low and high speed side, demonstrating that the torque specification has been met.

TABLE III
MAIN GEOMETRICAL DIMENSIONS

Dimension	mm
Z_m	10
Z_{fpm}	20
Z_y	20
Z_{ag}	2
R_{out}	250
R_{in}	175

The final mechanical design of the single stage axial magnetic gear is shown in Fig. 11.

B. D7.2 A review of Life Cycle Assessment on WEC.

This report presents a literature review within the LCA framework across their full lifecycle, including manufacturing, installation, O&M, decommissioning and disposal. The objective is to identify trends, key impacts, tools, databases, and methodological approaches used in existing assessments of wave energy technologies, providing valuable insights for comparison with the MEGA WAVE PTO concept.

This study follows a structured approach to evaluate the life cycle environmental impacts of various WEC concepts, provide insights into current WEC technologies and establish a baseline for future comparisons once the MEGA WAVE PTO concept is implemented.

The first stage involves desk-based research on existing LCA studies covering different WEC designs, including peer-reviewed research papers, technical reports, and

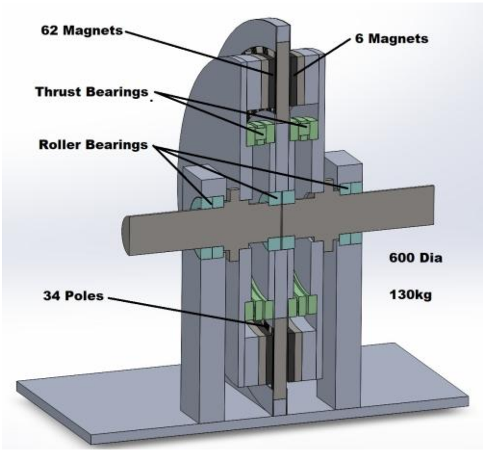

Fig. 11. Final assembly drawing of the single stage gear.

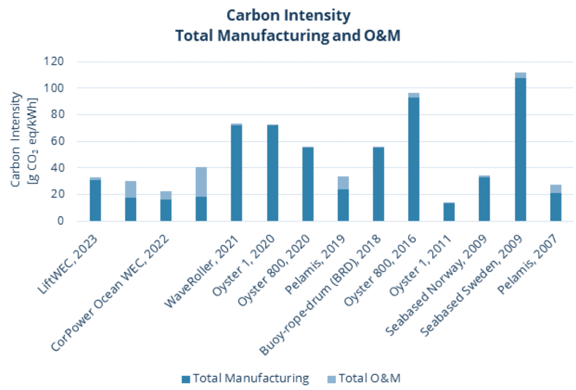

Fig. 12. Literature review: carbon intensity of total manufacturing and O&M for wave energy converters.

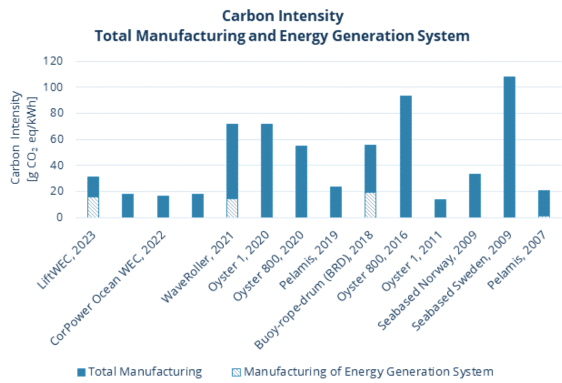

Fig. 13. Literature review: carbon intensity of total manufacturing and manufacturing of energy generation system for wave energy converters.

industry publications. Studies were selected based on strict criteria, prioritising those that adhere to established LCA methodologies such as ISO 14040/44 and provide a comprehensive life cycle assessment of WEC technologies. Particular attention was given to studies reporting carbon footprint (g CO_2 eq per kWh generated) and net energy consumption (MJ per kWh generated), as metrics to be used to benchmark the MEGA WAVE PTO in future assessments. Where necessary, results have been adjusted to ensure consistency across different functional units, improving comparability. The search prioritised studies that cover the full life cycle stages:

- Manufacturing: Analysis of raw material extraction, processing, component fabrication, and transportation from the manufacturer. Key data includes material composition (e.g., steel, composites, polymers), as well as emissions and energy use from production processes and logistics.
- Installation: Impacts related to transportation and deployment at the site, particularly emissions from installation vessels.
- Operation & Maintenance (O&M): Evaluation of maintenance strategies, intervention frequency, servicing-related emissions, spare parts replacement rates, and energy yield during the operational phase. This phase is particularly important for future comparison, as any improvements in downtime reduction from the MEGA WAVE PTO will provide comparative insights against existing benchmarks.
- Decommissioning & End-of-Life (EoL): Assessment of dismantling, recycling, and material disposal impacts. This phase is especially critical for comparison, as different EoL strategies, and system boundaries can significantly affect final results.

The assessment reveals that manufacturing is the dominant contributor to lifecycle emissions, while O&M impacts vary significantly, as indicated in Fig. 12. Some studies reported minimal emissions related to maintenance interventions, while others highlighted substantial contributions, particularly in scenarios with more frequent unplanned interventions. Nearly half of the studies reviewed report O&M contributing less than 5% to total carbon intensity, while in contrast, CorPower [16] and Pelamis [17] [18] studies show O&M exceeding 25% of total lifecycle impacts. Notably, CorPower reports O&M contributing over 52%, reflecting a worst-case scenario with a high estimate of unplanned annual failure rates.

This significant discrepancy in O&M impact estimates suggest that offshore operations are often inaccurately estimated or misrepresented in LCAs. Refining operational profiles to account for realistic failure rates, stoppages, and vessel requirements could provide a more accurate assessment of environmental impacts and help identify key hotspots. The sensitivity of O&M impacts underscores the importance of reliable maintenance strategies, which is a key focus of the MEGA WAVE PTO innovation.

Additionally, variability in system boundaries, impact assessment methods, and assumptions related to material and disposal credits, EoL strategies, and offshore operations, were identified as critical factors affecting comparability across studies. The modular approach in MEGA WAVE PTO proposes benefits in manufacturing and O&M.

A comparison of carbon intensity in manufacturing and O&M has been made for a number of devices, although only limited information on the carbon intensity specifically for PTO or energy generation system was found.

Fig. 13 explores the significance of manufacturing impacts specifically related to the energy generation system, though such breakdowns were often missing or lacked sufficient detail in the available literature. As a result, further analysis is needed to accurately compare these elements with the MEGA WAVE PTO concept. While no specific LCA results were found publicly available for the reference WEC technologies selected for comparison—Pure Marine, Mocean Energy, and Carnegie Clean Energy—the studies reviewed provide a valuable range of results that will serve as a baseline for evaluating the MEGA WAVE PTO concept. This allows for an approximate yet meaningful comparison to contextualise its potential advantages and areas for improvement within the broader wave energy sector.

V. Conclusion

The MEGA WAVE PTO project is a 4 year project due to finish in May 2028. An overview of the project has been presented in this paper with some initial results from the two deliverables completed in year 1. An all electric power take off is being developed for wave energy incorporating multi-stage magnetic gears integrated with the modular CGEN generator technology and modular power converters. Expected benefits include high efficiency, flexible control, reduced O&M costs leading to savings in carbon footprint and LCoE. The project team will update on progress at future EWTEC meetings and via the project website.

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