HiDrive

WES Power Take Off Stage 3

Public Report (D7.8)

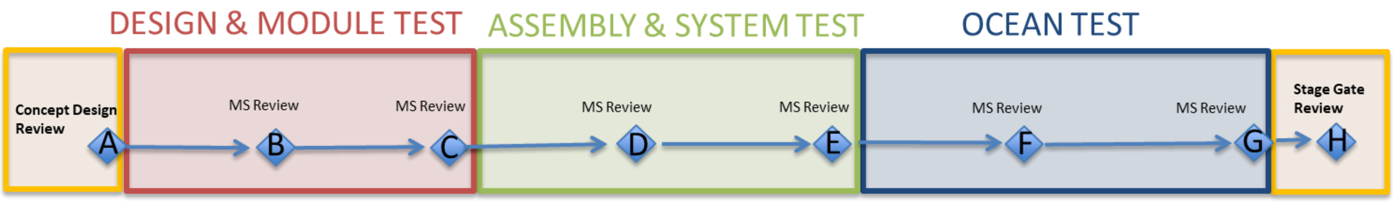
CorPower Ocean AB

This project has been supported by Wave Energy Scotland

1. Project Introduction

The primary purpose of the HiDrive project is to reach a reliable and proven PTO design that can produce energy at low cost and survive the conditions at any potential wave energy site in European waters. The CorPower Ocean PTO is built into a buoy type point absorber and attached to the sea bed with a taut leg mooring. The PTO operates in resonance with the incoming wave and can thus extract a much larger amount of energy than a passive floating WEC device. The resonance control is also used to allow the buoy to become transparent to high storm waves by detuning the motion of the buoy thus absorbing less energy, causing less tension to the mooring and lower forces on the PTO. The PTO and the resulting WEC is light resulting in higher structural efficiency (energy output/ton) of device compared with existing competing WEC designs. This light design and its surface operated mooring connection allows the WEC to be installed and replaced using small workboats without any intervention needed from diver or work class ROV.

The HiDrive program was divided into eight milestones comprising on three major phases. Upon completion of the concept design review with all stakeholders in Stockholm, the design and unit test phase began. Once the individual modules had completed acceptance testing and essential sub-system testing had been completed, the program advanced to full system assembly and dry testing in the Hardware-In-the-Loop (HIL) test rig. This phase ran until the system had completed testing representative sea states and satisfactorily accomplishing a two-week endurance period. At this time the system was transported to Scotland where the HiDrive program advanced to the final stage, including the incorporation of the Orkney based workshop and commenced ocean testing at the EMEC Scapa Flow nursery site. Finally, test and performance data were compiled, and a stage gate review process marked the completion of the HiDrive program.



The below table illustrates the eight HiDrive program milestones:

ID	Milestone Title	Associated Activities
MS A	PTO and HIL rig design review completed	Concept design complete
MS B	Key component purchase orders placed	Key components ordered, supply contracts signed
MS C	Initial system assembly and cross-component testing started	Module FAT complete; moving to system level integration & test
MS D	PTO rig FAT protocol completed	PTO system integration and cross-component testing complete, starting PTO-HIL whole system testing
MS E	Dry rig test program Phase 2 – completed	Complete system performance test in Stockholm
MS F	Final Stage 3 PTO design report	System delivered and assembled in Orkney, commencing wet test phase
MS G	Testing completed	Wet test results incorporated into calibrated models
MS H	Stage 4 FEED & Stage 3 results reported	All tests complete and documentation delivered

The HiDrive program was performed by a consortium consisting of CorPower Ocean (CPO), Iberdrola Engineering & Construction (IEC), the European Marine Energy Centre (EMEC), and the University of Edinburgh (UEDIN). CorPower Ocean was the project lead responsible for device development and testing. EMEC was responsible for risk-assessment and best practice support on deployment and testing, Iberdrola Engineering & Construction for design basis and certification, and University of Edinburgh for LCOE and numerical modelling. The Stage 3 activities were supported by Wave Energy Scotland, KIC InnoEnergy and the Swedish Energy Agency.

The market introduction of CPO's WEC technology follows a structured five-stage verification process, established as best practices for ocean energy technology by the IEA-OES, ETIP Ocean and Wave Energy Scotland. It involves step-wise validation of survivability, performance, reliability and economics starting with small scale prototypes in Stage 1, continued by sub-system testing and then fully integrated WEC in increasing scales up to array demonstration in Stage 5. The purpose is to address risks in a managed way early in the product development process, where costs are still limited due to smaller device scale and team size. The current Stage 3 program with ocean deployment in Scotland follows the prior testing of multiple prototypes in smaller scales performed in Portugal, France and Sweden since 2012, and thousands of hours of numerical simulation work.

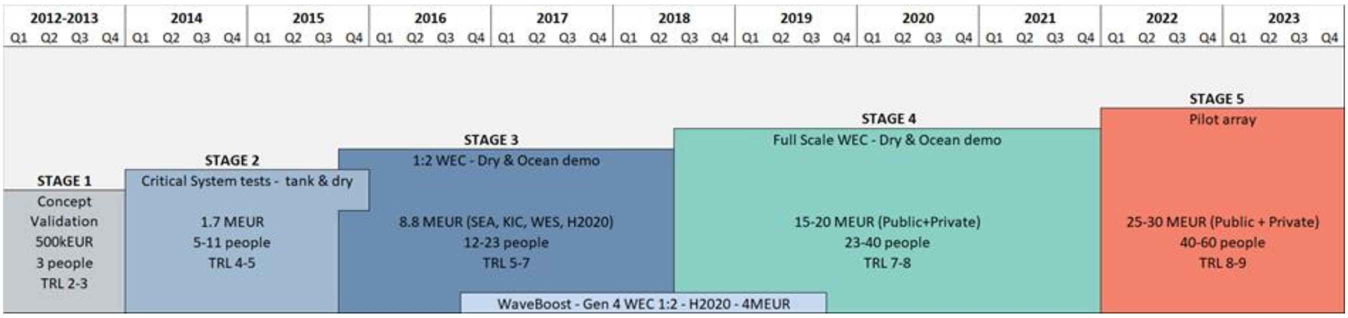


Figure 1 CPO's market introduction plan in 5 stages according to IEA-OES/EquiMar best practice

As of Q2 2018, CPO concluded the final phase of its stage 3 pilot program; reporting the outcomes while now preparing for the next phase of full scale deployment in a first pilot array in collaboration with leading partners across the value chain. The Stage 3 program has taken a large scale (1:2) Wave Energy Converter system through structured verification by dry testing in CorPower's machine hall facilities in Stockholm, followed by ocean deployment at the European Marine Energy in Orkney (Scotland).

2. Description of Project Technology

The CPO WEC is of point absorber type, with a heaving buoy on the surface absorbing energy from ocean waves and which is connected to the seabed using a tensioned mooring line. Novel phase control technology makes the compact devices oscillate in resonance with the incoming waves, strongly amplifying the motion and power capture. This offers five times more energy per ton of device compared to previously known technologies. The high structural efficiency allows for a large amount of energy to be harvested using a relatively small and low-cost device, providing competitive cost-of-energy. The system has improved survivability in storms, thanks to its inherent transparency to incoming wave energy, when detuned. Generators and power electronics are standard components known from the wind industry, enabling well known grid connection architecture. The buoys operate autonomously by a programmable logic controller located inside the device, with an interface for remote control and data acquisition to shore over radio-link. The step-change increase in structural efficiency and provides a path for wave energy to overtake wind turbines in structural efficiency and competitiveness.

Figure 2 Illustration of the CPO WEC concept

The CorPower WEC converts renewable energy from waves into electricity through the rise and fall as well as the back and forth motion of waves. A composite buoy, interacting with this wave motion, drives a Power Take Off (power train located inside the buoy) that converts the mechanical energy into electricity. The WEC consists of a light buoy connected to the seabed through a power conversion module and a tension leg mooring system. By means of novel and patented technologies the CPO WEC moves in resonance with incoming waves, making it move in and out of the water surface. Three novel and patented technologies enabling this is described below.

1. Pneumatic pre-tensioning technology: The pre-tension system provides downward force on the buoy from an air pressure acting in a pneumatic cylinder. This replaces mass that would otherwise be needed to balance the buoyancy at midpoint. As a result, the natural period of oscillation of the WEC is reduced, providing a period of oscillation which is shorter than all ocean waves. This natural state of the machine is the detuned mode where the device has little response to incoming wave.
2. WaveSpring phase control technology: WaveSpring is a pneumatic module providing a negative spring function between the PTO and the buoy. The pushing force acting as a snap-through mechanism results in a system with an inherently resonant response over a wide bandwidth. Optimised phase control is provided without information on incoming waves, and without any active control. Since the WaveSpring function is dynamic it can be disabled in storms, detuning the device to give reduced loading and improved survivability.
3. Cascade gear technology: The linear motion of the buoy is converted into electricity by the mechanical drive train located inside the buoy. A key component is the Cascade gearbox, which efficiently converts linear motion to rotating motion. It has a design principle similar to a planetary gearbox, which divides a large load onto a multiple of small gears which allows conversion of linear-to-rotation or rotation-to-linear motion.

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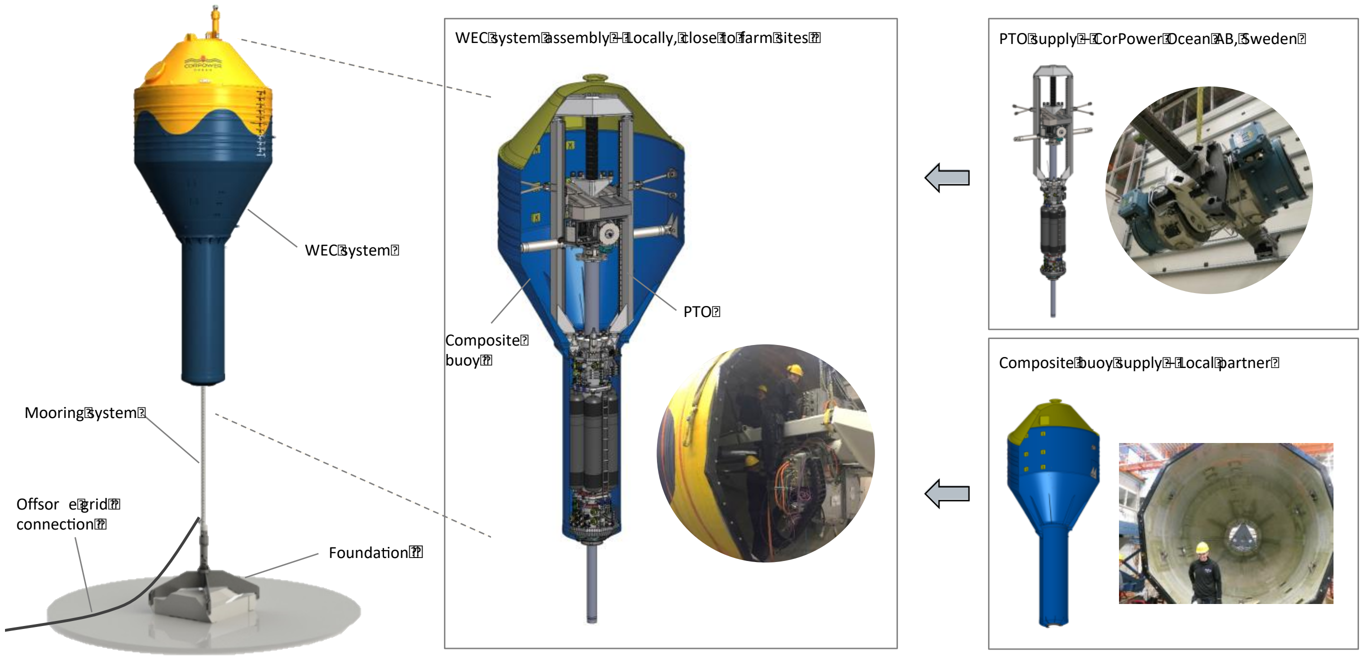


Figure 3 WEC sub-systems and supply chain overview

The associated wave farm concept is based on combining hundreds or potentially thousands of units in arrays, with a common grid export cable connected to the existing on-land grid, similar to an offshore wind farm. The concept allows for mass production to drive down the cost per unit, and a maintenance scheme based on the replacement of entire units. This avoids performing service activities in the harsh offshore environment and offers improvements in farm uptime and an overall reduction of O&M cost. The replacement scheme is enabled by the small physical size and limited cost per system, allowing simple handling and reasonable investment in spare units.

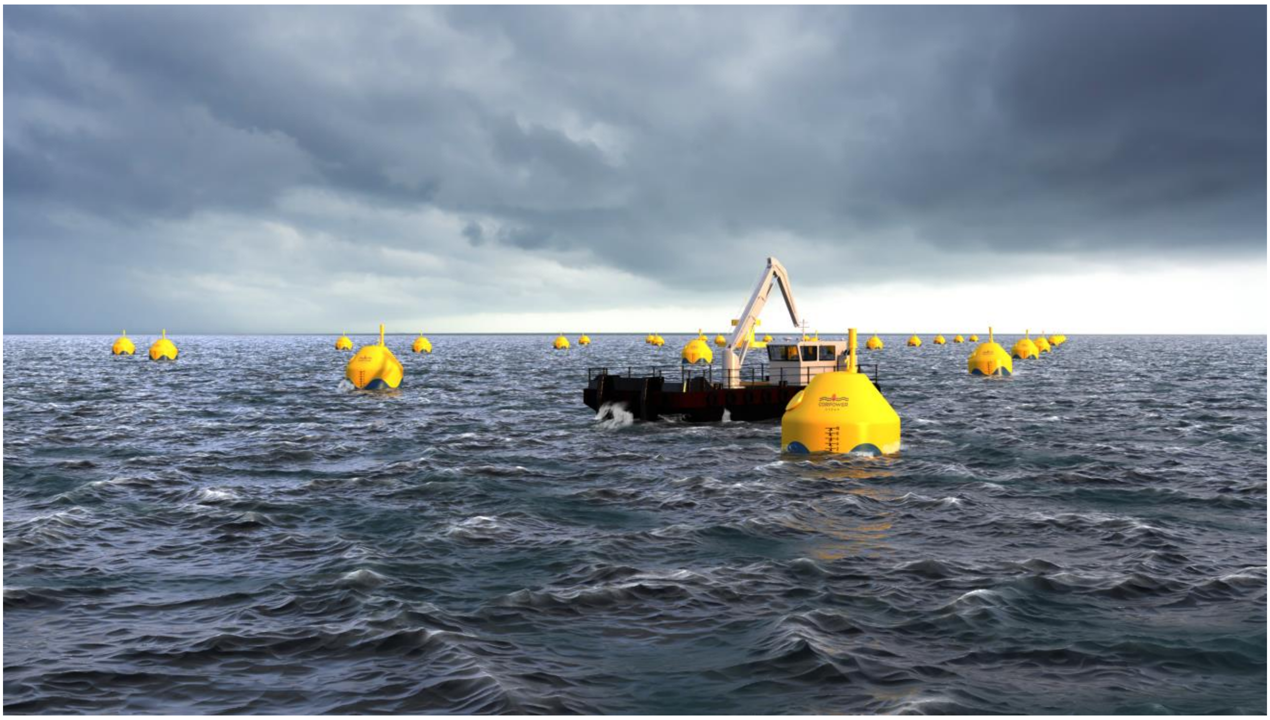


Figure 4 Illustration of the CPO WEC farm concept

3. Scope of Work

By implementing a step by step approach in the design validation and by performing detailed rig testing the consortia aimed at having a well debugged and stabilized system prior to ocean deployment. The system performance and control software were tested over the full range of load conditions using a new HIL-rig supplied by subcontractor Cascade Drives AB. By identifying and correcting any issue that can be found on-land, the following ocean tests in sheltered waters was de-risked. The dry rig was to be used for periodic re-qualification and health check on the PTO between ocean test cycles.

The high-level objectives with Stage 3 prototype verification:

1. Prove that the CPO WEC technology can offer a step-change improvement in absorption performance, conversion efficiency and CAPEX over current state-of-the art;
2. Verify the reliability, operability and scalability of the solution;
3. Validate a realistic path to LCOE below 150 GBP / MWh after having less than 200MW installed;
4. Take advantage of the best available guidance and methodology with respect to risk management, test methods and standards;
5. Develop a rig for dry Hardware-In-the-Loop (HIL) testing of WECs. The rig being capable of simulating wave loading over the full range of sea states and instrumented for detailed characterization of WEC performance;
6. Develop methods for dry qualification of all key PTO functions in the HIL-rig prior to wet-testing, and re-qualification of the PTO between cycles of wet testing;
7. Design a PTO that can be effectively integrated into different WECs;
8. Verify each of the target outcomes by dry testing of the PTO, followed by wet testing in Scapa Flow nursery site;
9. Monitor PTO condition by intermediate dry re-qualification between wet test cycles.

CPO together with its sister company Cascade Drives AB (spun out of CPO to commercialize the cascade gearbox technology for industrial applications outside of ocean energy) has developed and commissioned an advanced rig for dry HIL-rig testing of resonant WECs. The 500kW peak capacity HIL-rig is capable of simulating wave loading over the full range of sea states and is instrumented for detailed characterization of WEC performance. Key specifications include:

- 3.5m active stroke
- 3 m/s peak velocity
- 200kN dynamic force with PID-controlled reference following of simulated hydrodynamic loads
- Real-time simulation model of wave/buoy interaction running in PLC environment

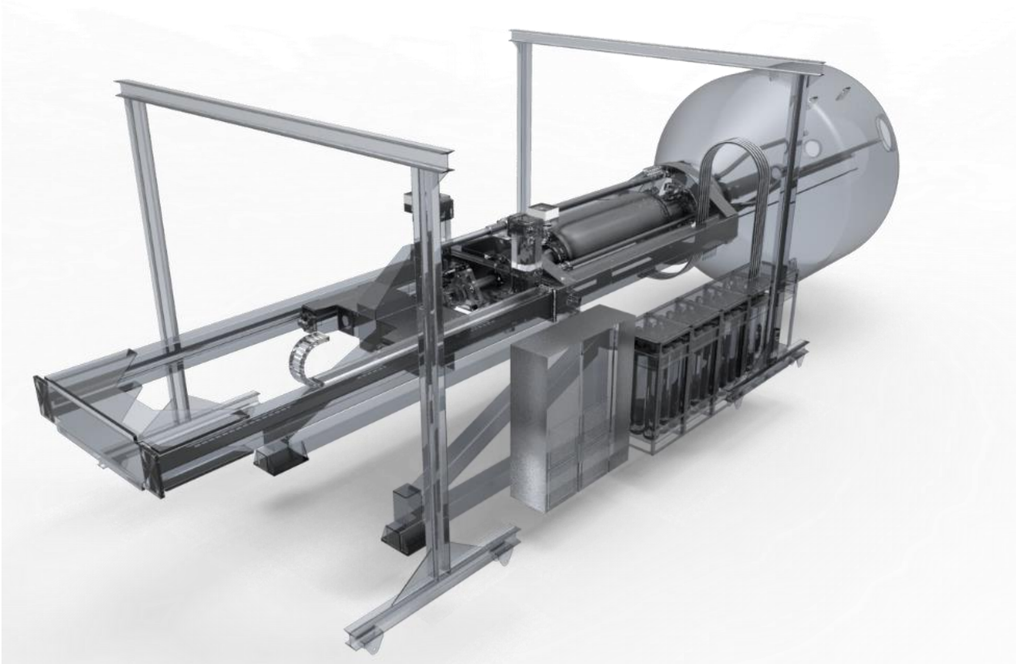


Figure 5 Stage 3 HIL-rig with C3 PTO and composite hull mounted. Electrical drive system on floor

The HIL rig was designed to run the WEC machinery in a controllable environment before operation in the ocean. During the dry test campaign, the HIL rig was used to test the machinery in all sea states that may be experienced at Scapa Flow, from normal operation sea conditions through to storms.

In the CPO WEC, the buoy and slide are constrained to move co-axially. The dynamics of the WEC machinery is then a function of the relative motion of these two bodies. In real-sea operation the buoy and slide move in both translation and rotation, under the influence of gravity, hydrodynamic forces and mooring forces. In the HIL rig the buoy is fixed and the slide is moved by the HIL rig motor. The slide moves such as to mimic the machinery dynamics of the system as it would work in the ocean, including accurate hydrodynamic loading with non-linear correction, for surge and heave motion combined.

Figure 6 Stage 3 WEC in CorPower dry Hardware-in-the-loop testing facility, Stockholm (Sweden)

The C3 PTO was put through a series of tests including:

- Function testing to verify and tune each specified function;
- Debugging and stabilization of the PTO;
- Performance testing, to verify the power production and efficiency of the PTO;
- Survivability testing in full range storm loading, verifying end-stop functionality, thermal and vibration behavior while operating under high loading;
- Non-interrupt testing to verify sufficient stability and uptime prior to ocean deployment.

By conducting validation of the C3 PTO in the HIL rig according to a structured plan, verification was accelerated at lower risk and cost than if done offshore. The dry test program was performed between April and November 2017 and resulted in a well characterized PTO contributing to a high stability and uptime for the C3 WEC considering a first-of-a-kind prototype. 708 test runs were registered, with 378 signals acquired in each test, providing more than 1 TB of data on the equipment. The innovative WaveSpring phase control method was verified, with sub-system efficiency of 99% at rated loading. Based on the measured performance of the PTO machinery and the calibrated numerical models resulting from it, the projected performance of the next generation C4 WEC could be slightly increased after the dry test compared to previous projections.

During this time EMEC was an integral part of the HIL rig testing and travelled to Stockholm on several occasions to work alongside the CPO team. HIL acceptance testing (with & without WEC attached) was completed with EMEC prior to commencing PTO performance testing; upon completion of PTO performance testing, data and numerical model calibration materials were shared with EMEC in order to obtain a Performance Statement.

Following completion of dry testing, the prototype device was transported by road and sea to Orkney where testing was planned at the EMEC Scapa test site, approximately 600 m offshore. The European Marine Energy Centre (EMEC) is a test centre, managing several test locations in Orkney. EMEC was established in 2003 to provide developers of wave and tidal energy converters with open sea testing facilities. The Scapa Flow site was selected for C3 ocean deployment due to its sheltered location which offered a wave resource suitable for the 1:2 scale device, and for access to nearby port facilities and local marine operators with previous experience of the sector.

The ocean test campaign was performed between January and June 2018 at the EMEC Scapa Flow site, Orkney. The purpose was to verify the survivability, functionality and performance of the fully integrated WEC system in a relevant ocean environment. Having an extensive mapping of the device behaviour and performance over a wide range of sea conditions from the dry testing, the key purpose of the wet testing was to verify the practical functionality of the device in the ocean environment, including auxiliary support functions such as station keeping, tidal range regulation, power export in microgrid configuration, communication to shore, remote control and associated operations and maintenance methods, while verifying motion and power production performance over a range of relevant sea states.

A gravity base anchor consisting of 8 concrete blocks arranged on a steel base plate was already on the EMEC test site. CPO commissioned the design and fabrication of a cross frame and winch to install over the concrete blocks, enabling anchoring of the WEC and tidal regulation of the device to maintain its position in the water as the tide changes. As part of the test programme, EMEC commissioned and installed a test support buoy (TSB), i.e. a micro-grid to support off-grid testing which is housed within a 10-foot container and installed on a 3-point moored pontoon.

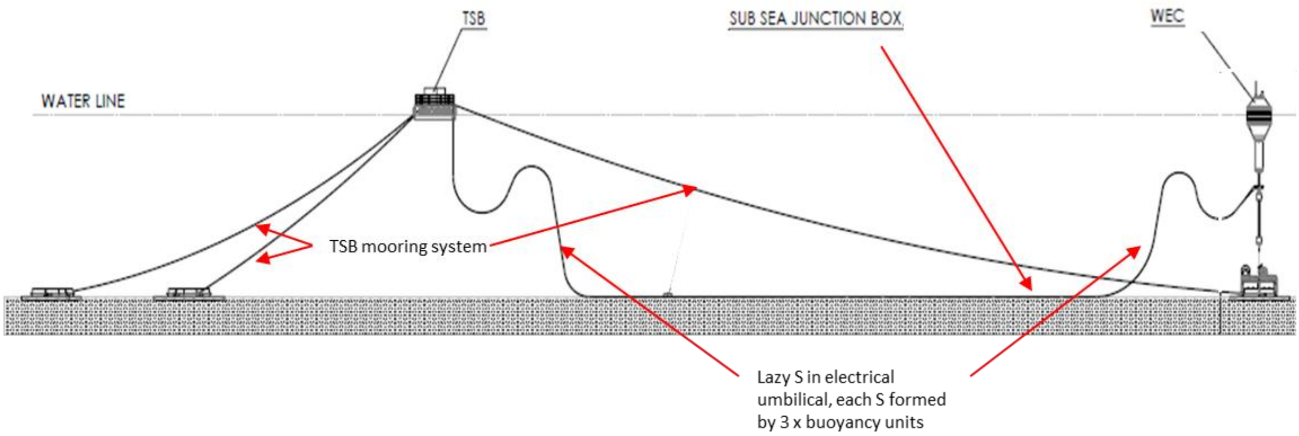


Figure 7: Illustration of the ocean setup for the C4 WEC ocean demonstration at Scapa Flow, EMEC wave test site

The micro-grid delivers power to and absorbs power from the WEC, which it is connected to via an electrical umbilical, using SMA Sunny Island inverters and TesVolt batteries. It also powers the winch system which is controlled by a hydraulic power unit (HPU) on the TSB, connected by approximately 200 m of hydraulic cables and an encoder cable. This solution (anchoring and tidal regulation) is not intended for subsequent iterations of the device, i.e. its sole purpose was to enable C3 device testing. The experience developed with the floating microgrid operation is relevant for future off-grid installations, such as aquaculture or oil & gas applications where remote installations may be powered by CPO WECs while floating microgrid units house energy storage.

The WEC was periodically brought to shore during the test period, demonstrating the CPO strategy for the rapid replacement of entire units rather than costly offshore maintenance.

During the ocean test period, CPO had access to an onshore workshop located in Kirkwall where the device could be housed and prepared prior to deployment, and periodic maintenance conducted during the test period. Detailed method statements were developed in close collaboration with Orkney marine operators, lifting contractors and EMEC, supported by lessons learned and best practice from the sector. CPO's operations team also has significant field experience from previous marine energy projects.

Figure 8 Stage 3 WEC during deployment at EMEC Scapa Flow test site

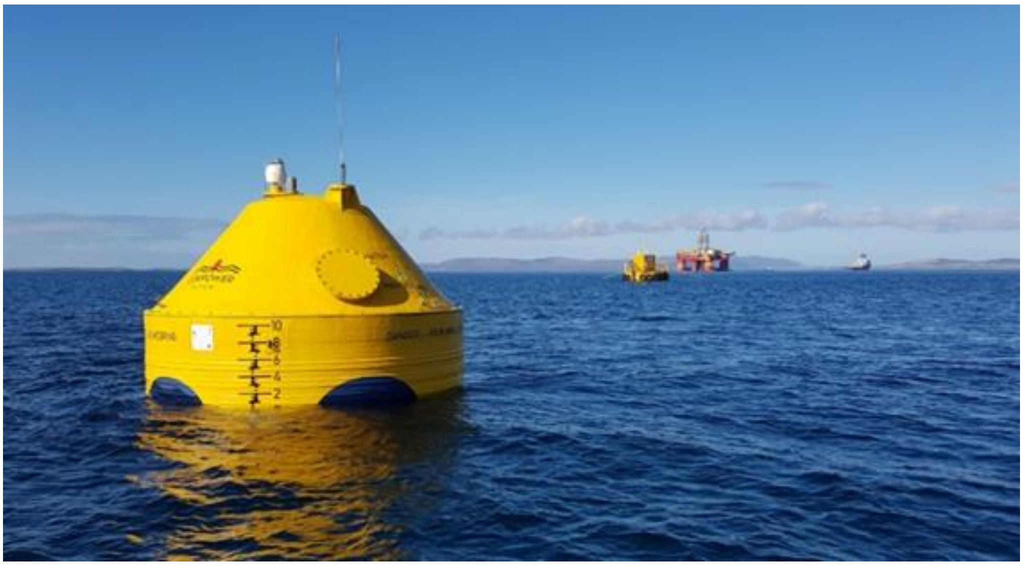


Figure 9 Installed C3 WEC at EMEC Scapa Flow test site

Ocean testing gave the following results:

Survivability: During January 2018 the survival mode of the WEC was first tested in waves up to 2.56m (equivalent to 5.12m in full-scale) and wind speeds up to 50 knots. In June the largest sea states were encountered, with the device operating in survival mode in up to 2.05m Hs, corresponding to individual waves close to 4m (equivalent to 8m in full-scale). The load shedding function was found to perform well, with load levels that did not inflict damage to the WEC and the detuned motion of the device kept well within boundaries.

Tuned operation. The performance of the tuned (resonant) operation mode was verified during the ocean testing over the relevant range of sea states, up to 1.38m significant wave height (equivalent to 2,76m in full-scale). The resonant motion is apparent, with the expected amplification of velocity and power capture verified. All sea states encountered in the ocean has delivered slightly higher power production compared to the projections from the simulation models. In the more energetic sea states the power delivery was a few percent higher than in numerical modelling calibrated after the dry testing, typically + 2-3%. In lower sea state the relative difference is larger. The results have provided further verification of the performance projections for the next full scale C4 system.

4. Project Achievements

The dry and ocean testing campaigns of the half-scale CPO C3 WEC have confirmed the design principles, operability and performance of this new type of resonance WEC. The innovative WaveSpring phase control method was verified, with sub-system efficiency of 99% at rated loading. The unique storm survivability method of detuning the device was verified. The resonant operation with WaveSpring was found to work reliably during ocean testing.

Following the dry test campaign, the WEC has shown stable operation with respect to specified functions during the ocean deployment, with good availability considering that it is first-of-a-kind prototype. Efforts during ocean testing was focused on stabilizing auxiliary sub-systems including the Microgrid, the tidal adjustment system, the anchor and umbilical cabling before arriving at an overall installation that could demonstrate all specified functions. A key lesson learned is that a more rigorous pre-qualification of such auxiliary systems, similar to the PTO dry testing, would have been beneficial to the program.

The test campaigns resulted in detailed calibration of in-house simulation models, which can now be expected to yield accurate projections of the full scale C4 and C5 WEC systems. Using the calibrated numerical models, and the design choices identified from Stage 3 lessons learned, the power output projections of next generation C4 and C5 machines has been slightly increased compared to the projections done prior to Stage 3 testing. Key results from Stage 3 are summarized in the figure below.

Important lessons were learnt, on an architectural level for the device concept, on sub-system design and on the performance and reliability of specific components that affect design choices for the next generation. The Stage 3 program has verified the key metrics AEP, AEP / ton and AEP / Force, Following the results, the LCOE projections for the technology has been updated (described in detail elsewhere), providing a clear path to reach competitive cost levels with other more established energy sources. A comprehensive certification program was initiated in Stage 3 resulting in the targeted Statement of Feasibility of the technology from DNV-GL.

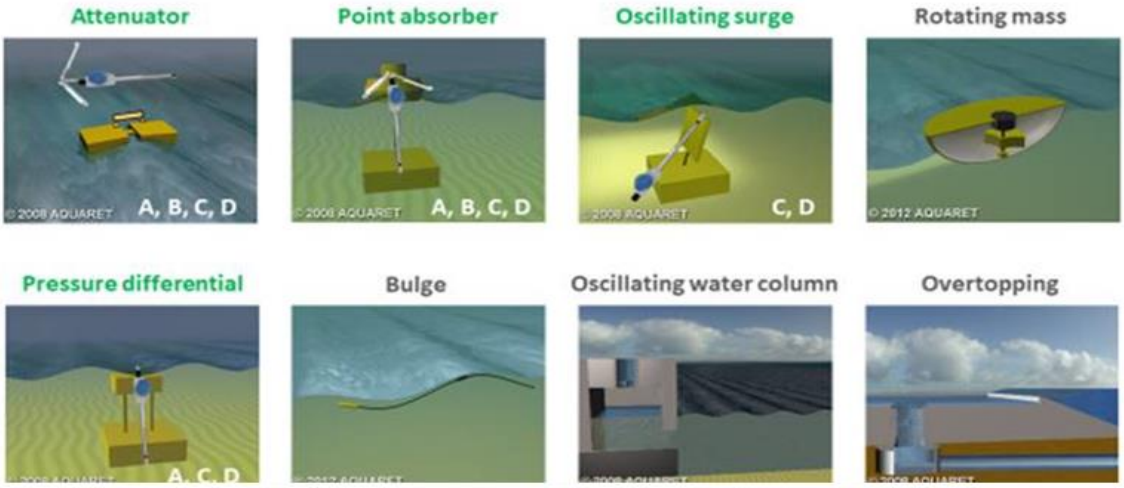
Dry testing of the WEC in a HIL-rig was associated with significant investment in effort and equipment but was of considerable value to the project. Debugging and stabilizing a new PTO by verifying each function in a controlled environment starting with gentle loading and low velocities, allowed the control and safety functions to be verified and tuned. Having built confidence at low sea states, ramping up to storm loading could then be done. Operating the equipment in the high load regime allowed adjustment and verification of the machine. Performing dry testing in a machine hall environment provided ease of access to equipment and a high degree of instrumentation improved understanding of machine behaviour, contributing to an effective test and stabilization program.

5. Applicability to WEC Device Types

CorPower's business model is based on supplying complete WEC systems to project developers. A potential longer-term potential business model that may enable rapid scaling of the business is to narrow the supply scope to the PTO where a majority of the current IP is located. With such business model, PTO units could be sold to multiple WEC integration customers around the world, where such WEC integration companies could focus on the marine interfaces and farm engineering while CPO maintains the main responsibility for the machinery inside the WECs. Collaboration with possible integration partners has been initiated. Partnering activities in the opposite direction, evaluating the opportunity of sourcing components from other wave developers that could bring improvements to the CPO WEC system has also been initiated, supporting the main business model of CorPower.

The following PTO components of CorPower have been identified as applicable for possible integration into the following WEC types:

A. Pretension system (low weight, high natural frequency of oscillation)
B. WaveSpring (inherent phase control)
C. Cascade Gear box (linear-to-rotation)
D. Temporary storage and conversion (Dual set of flywheels & generators)



WEC type	A	B	C	D
Point absorbers, neutrally buoyant		☺	☺	☺
Point absorbers, pretensioned	☺	☺	☺	☺
Point absorbers, submerged (Pressure differential)	☺		☺	☺
Attenuators, surface piercing	☺	☺	☺	☺
Attenuators, submerged (bulging)				
Pitching devices with geometric or large-body reference	☺	☺	☺	☺
Pitching devices, floating (rotating mass)				
Oscillating wave surge devices (hinged flap)			☺	☺
Oscillating water columns				
Overtopping devices				

6. *Communications and Publicity Activity*

Conferences & Events

- Ocean Energy Europe 2015, Dublin, Ireland, EMEC booth presentation
- World Water Week 2015, Stockholm, Project presentation
- All-Energy 2016, Glasgow, Scotland, EMEC booth presentation
- ICOE 2016, Edinburgh, Scotland, EMEC booth presentation
- Green Connections 2016, San Diego, CA, USA, "High Efficiency Wave Power" Presentation
- Ocean Exchange 2016, Savannah, GA, USA, "High Efficiency Wave Power" presentation
- Wave Energy seminar & Grand Opening, CorPower C3, 2017, Stockholm, Sweden
- Ocean Energy Europe 2017, Nantes, Frances, “Wave Power Take Off - Have we cracked it?” presentation
- Shell New Energy Challenge 2017, Amsterdam, The Netherlands
- Ecosummit, Berlin, 2017, Project presentation
- Ocean Meeting 2017, Lisbon, Portugal, "Harvesting Energy from our Oceans"
- All Energy 2018, Glasgow, Scotland, “Resonant wave energy harvesting – CorPower C3 at EMEC”
- ICOE 2018, Cherbourg, France, “The power of resonance”

Publications

- de Andres A, Maillet J, Hals Todalshaug J, Möller P, Jeffrey H. On the Optimum Sizing of a Real WEC From a Techno-Economic Perspective. ASME. International Conference on Offshore Mechanics and Arctic Engineering, Volume 6: Ocean Space Utilization; Ocean Renewable Energy

- de Andres, A.; Maillet, J.; Hals Todalshaug, J.; Möller, P.; Bould, D.; Jeffrey, H. Techno-Economic Related Metrics for a Wave Energy Converters Feasibility Assessment. Sustainability 2016, 8, 1109.

- Hals Todalshaug, J.; Steinn Ásgeirsson, G.; Hjálmarsson, E.; Maillet, J.; Möller, P.; Pires, P.; Guérinel, M.; Lopes, M. Tank testing of an inherently phase-controlled wave energy converter, International Journal of Marine Energy, Volume 15, 2016, Pages 68-84, ISSN 2214-1669

Press releases

- http://renews.biz/108353/simply-blue-picks-wave-winners/
- https://content.yudu.com/libraryHtml/A42yym/WaveampTidalEnergyNe/reader.html
- https://www.nyteknik.se/energi/i-host-sjosatts-vagkraftverket-6855285
- http://www.corpowerocean.com/wp-content/uploads/2018/01/CorPower-deploy-C3-Wave-Energy-Converter-at-EMEC.pdf
- https://www.oceanenergy-europe.eu/industry-news/corpower-expands-in-scotland-preparing-for-orkney-deployment/
- http://www.innoenergy.com/corpower-s3-delivers-first-power-to-the-grid/

Others

- Webinar: Funding Ocean Energy Technology Development Using Pre-Commercial Procurement and Stage-Gate Development Processes, 05/10/2017, https://www.etipocean.eu/events/webinar-4/
- Seminar at OEE2017 Conference: Wave Power Take Off - Have we cracked it? https://www.etipocean.eu/events/seminar-at-oee2017-conference-wave-power-take-off-have-we-cracked-it/
- https://www.youtube.com/watch?v=nV9jC5TLHZk
- https://www.youtube.com/watch?v=CqsMu2nHltg

7. Recommendations for Further Work

Taking advantage of not being a first mover in the sector, CorPower has analysed other developer's lessons learned as well as utilising in-house experience when designing the go-to-market strategy. It has also been reviewed with utilities, academic experts and industry leaders that have developed own technologies, both successfully and unsuccessfully. The conclusion is clear, to succeed in this challenging field, with the introduction of a reliable product with the least time, money and risk, we should continue the structured product verification process until reaching a fully bankable product.

The activities leading up to this is divided in the following two remaining Stages:

- Stage 4 – Demonstration and certification of single device full scale C4 WEC, planned for 2018-2021. Taking the technology from TRL 7 to TRL 8.
- Stage 5 – Demonstration and certification of pilot array with three C5 WECs, planned for 2021-2023. Taking the technology from TRL 8 to TRL 9.

The Stage 4 & 5 demonstration project aim at having at least three operational devices demonstrated in the pilot farm by 2023, delivering electricity to the grid with full certification and validation of availability and performance, leading to a warranted and bankable product. Reaching this Stage 5 gate will provide the data and certificates needed to allow warranties and insurances to be structured so that 10-30MW farms can be constructed thereafter.

8. Useful References and Additional Data

CorPower Ocean, http://www.corpowerocean.com/

The European Marine Energy Centre, www.emec.org.uk/

The University of Edinburgh, https://www.ed.ac.uk/

Iberdrola Engineering & Construction, https://www.iberdrolaingenieria.com/ibding/

Publicity Material

Filename	Media Type	Description
corpower 2.jpg	Picture	Picture of the CPO WEC deployment at Scapa Flow
corpower 3.jpg	Picture	Picture of the CPO WEC deployment at Scapa Flow
corpower 4.jpg	Picture	Picture of the CPO WEC deployment at Scapa Flow
corpower 5.jpg	Picture	Picture of the CPO WEC deployment at Scapa Flow
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