Advanced Archimedes Waveswing

WES Novel Wave Energy Converter
Stage 3 Project

Public Report

AWS Ocean Energy Ltd

This project has been supported by Wave Energy Scotland

Project Introduction

1 General

1.1 Overview

The advanced Archimedes Waveswing™ is a submerged heaving point absorber Wave Energy Converter (WEC) designed for offshore wave energy production. This report provides an overview of work carried out by AWS Ocean Energy Ltd to further investigate the potential of this device as Stage 3 of the Wave Energy Scotland (WES) Novel Wave Energy Converter (NWEC) programme. The key objective of the project was to design, build and test at sea a partial scale Waveswing. This work was completed over a period of three years with the WEC being deployed at the European Marine Energy Centre (EMEC) scale wave test site in Scapa Flow in March of 2022. Details of the previous Stage 2 project are provided in report reference *WES_NW21_AWS_PublicReport*, available in the WES library (Grey, December 2018). The Waveswing technology is described in §2 of this report.

1.2 Overall project objectives

The Stage 2 project completed the Front-End Engineering Design (FEED) of a nominally half-scale Waveswing WEC, whilst also identifying key technical risks that should be addressed through at-sea testing and demonstration. Further to the Stage 2 work, AWS Ocean Energy identified an opportunity to further reduce cost, risk and complexity of the WEC by re-positioning the rolling seal to eliminate the active annular water column. This however introduced some minor uncertainty in the power performance and previous validation of the numerical model for the WEC. Finally, it was recognised that the next step in the technology development road-map was likely to be the construction of a pre-commercial prototype and hence it would be necessary to confirm the market requirements and to seek potential commercial partners during the partial-scale test phase.

Bearing these points in mind, the specific objectives of the project were:

- To carry out a further tank-test campaign to confirm the impact on performance of introducing a seal in the floater-silo annulus;
- To upgrade the numerical performance model for the WEC and to validate this using both tank and at-sea test data;
- To specify, design, build and commission a fully-functioning Waveswing WEC at partial scale for the purposes of deployment and testing at EMEC's Scapa Flow scale wave test site;
- To deploy, operate, test and recover the WEC in order to address key technical uncertainties including:
    - The feasibility of the marine operations for deployment and recovery;
    - The functionality of the rolling seal;
    - The functionality of the tidal compensation system;
    - The functionality of the PTO system, including the ability to implement AWS Ocean Energy's advanced control algorithm for optimal power capture;
    - The behaviour and stability of the internal air system;
    - The overall operability, survivability and resilience of the WEC in a real operational environment;
- To investigate potential markets for the technology and to attempt to engage commercial partners and customers to support the ongoing development and demonstration of the technology in subsequent stages.

Whilst the Coronavirus pandemic caused some delay to the project and impacted on the way in which the project team functioned, the objectives were all met and the detailed achievements are set out in §4 below.

1.3 Project team

The project, including the extended test period was carried out by a broad team over a period of 46 months, with key activities and responsibilities as follows:

Table 1: Project Team

Team member / organisation	Responsibilities
AWS Ocean Energy	Overall project lead and management, technical direction, economic modelling and test site preparatory work.
Quoceant	Key engineering subcontractor with responsibility for detailed engineering design of the WEC and concept design of the marine operations.
4c Engineering	Provision of seconded personnel to AWS and general support on engineering tasks and site testing.
K2M	Development of new numerical model and cross-validation against previous models and tank data.
Sequentec	Design, manufacture, programming and site commissioning of the control system
Malin Group	Fabrication, integration and completion of the WEC.
SRP	Design and production of the Rocksteady mooring connector
Trelleborg	Design and production of the rolling seal
Hydrosafe	Provision of health and safety advisory services
Green Marine	Provision of marine operations services for deployment and recovery of WEC and anchor
EMEC	Provision of test site infrastructure, test-support buoy and micro-grid
Concept Cables / Scorpion Oceanics	Provision of umbilical cable and wet-mate connectors
Leask Marine	Installation of umbilical cable.
Stoddart Crane Hire	Provision of lifting services and general facilities during dry-test phase
MacIntosh Plan Hire	WEC transportation
Orcades Marine Management Consultants	Provision of third-party verification for moorings and marine operations, plus operational support.
Heddle Construction	Provision of lifting services and plant hire during wet-test phase
Alfik Shorebase Services	Shore support and provision of ROV surveys

The successes achieved during the project demonstrated the value of bringing together a team with such deep understanding and experience of wave power development.

2 Description of Project Technology

2.1 General description

The Archimedes Waveswing™ is a submerged heaving point absorber Wave Energy Converter designed for offshore wave energy production. The system is configured to achieve a very low impedance across a broad wave period range in order to be responsive across typical wave climates. The key components of the Waveswing are as follows:

- An inverted canister (the 'Floater') enclosing a volume of gas, and typically being submerged to a depth required to achieve 3.0m of clearance to the free surface in its extended (raised) condition. The Floater is free to move vertically, subject to the constraints of a power take-off system, linear guidance and end stop equipment. The crown of the Floater provides the wave absorbing surface;
- An inner telescopic canister (the 'Silo'), concentric with the Floater and together with the Floater and the rolling seal, forming a single sealed chamber. The Silo is connected to the Floater via the power take-off (PTO) system and the lower part of the Silo is restrained by e.g. a mooring system;
- The PTO system which controls the relative motion between the Floater and the Silo, controls the forces on the Floater so as to optimise wave energy absorption and converts the absorbed power to electricity;
- An environmental control system which regulates the internal gas pressure within the Waveswing;
- A variable length tether mooring connection, which can compensate for tidal variations, connects the Silo to the Anchor via a suitable quick-release connector; a suitable anchor resists the WEC loading and provides the station keeping capability.

The key system components are shown in Figure 1 below and the completed partial scale Waveswing device (PSWD) is shown in Figure 2 overleaf.

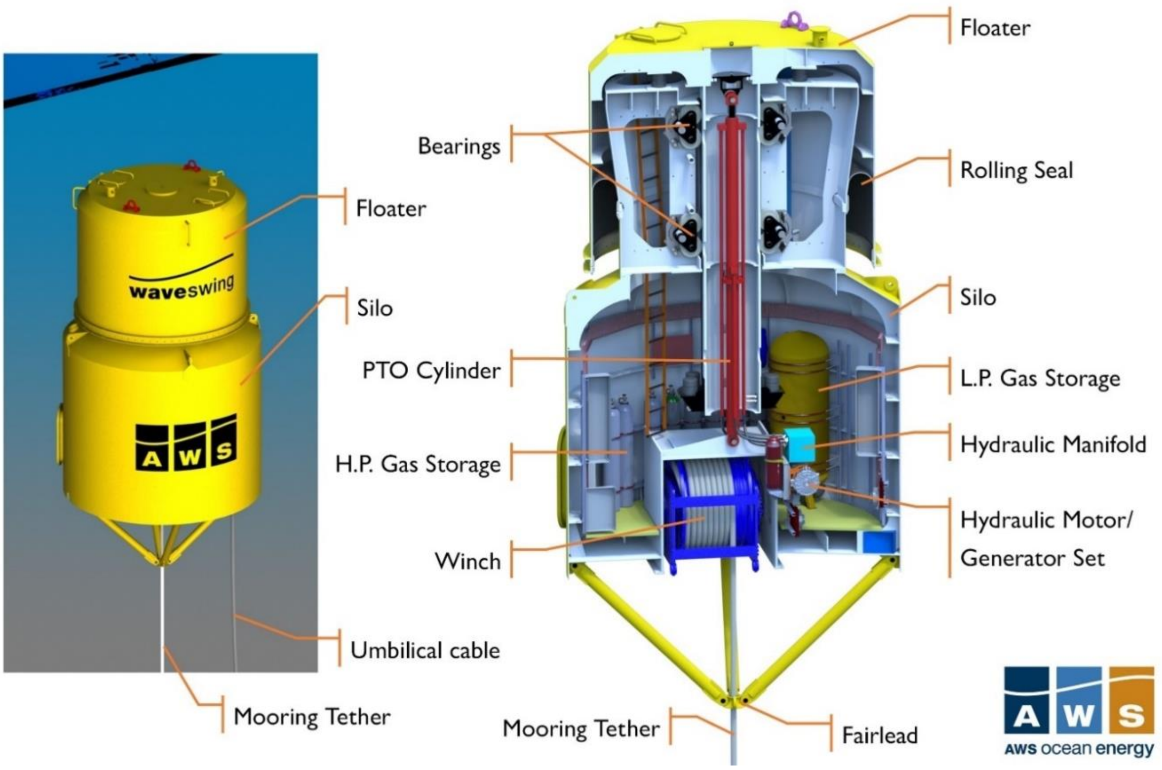

Figure 1: Key components of the Waveswing partial-scale demonstrator

Figure 2: Waveswing during installation in Scapa Flow

2.2 Operating principle

Operation of the Waveswing™ is as follows: At mid-stroke, internal pressures are such that the device is in static equilibrium. An approaching wave crest increases the external pressure on the Floater causing an imbalance in forces and hence the Floater moves down-wards causing a further build-up of hydrostatic pressure on the floater surface (i.e. a negative hydrostatic spring response). This is counteracted by the compression of the internal Floater air thus balancing the external hydrostatic and hydrodynamic forces. The floater continues to compress until the force equilibrium is re-established. The disconnect from a conventional surface piercing hydrostatic spring results in a conveniently soft spring which can achieve a multiplication of the wave height without the need for strong resonant behaviour. The wave is absorbed due to the void created through contraction of the WEC volume, in particular due to the wave radiating potential of the floater surface closest to the free surface. Note also that due to the up-facing orientation of the wave-radiating surface, that diffraction forces on the oscillator are supplementary (and not counter-acting) to wave Froude-Krylov forces. This is another fundamental benefit of the Waveswing configuration over surface piercing oscillators. The process is reversed for a wave trough. The very 'flat' spring curve achieved by this configuration coupled with the low inertia Floater means that the impedance of the device is inherently low, and the response is very broad-banded.

2.3 Shut-down and survival

For shut-down or survival the Floater is retracted to bottom-dead-centre and locking pins are engaged in the floater column. The WEC is winched lower in the water-column to reduce wave forces and remove the possibility of surface piercing in large wave troughs. The device pitches on its tether in order to shed loads in large waves.

2.4 Technology advantages

The major advantages of the Waveswing technology are as follows:

- Survivability – the device has several features that improve survivability including the sub-sea location and ability to achieve mechanical shut-down by removing the differential pressure actuation forces by depressurising the interior;
- Energy capture – the operational principle of the device allows significantly more energy to be captured per unit volume than that which is available from a surface-piercing device;
- Scale-ability and multi-absorber integration potential – a single Waveswing absorber can be scaled to 500kW or more whilst maintaining excellent energy capture potential. The physical arrangement of the Waveswing lends itself to integration into a multi-absorber platform capable of achieving multi-MW outputs;
- Potential for low LCOE – the potential for multi-absorber structures with all maintainable parts being accessible at sea, together with high energy capture potential create the necessary conditions to achieve a low levelized cost of energy;
- Very low environmental impact – the high array density, single-point moorings and sub-sea location ensure very low environmental impact and potentially higher stakeholder acceptance;
- Low technology risk – the device has low technology risk due to the simple operating principle and the fact that all sub-systems have been proven in service at sea.

Following this detailed investigation, the project team now believes that the Waveswing offers one of the very best prospects for delivery of affordable energy from the power in ocean waves.

3 Scope of Work

The Stage 3 project was primarily intended to demonstrate the Waveswing technology at partial scale through open-water testing and to gather data and operational learnings upon which to base future design and development work. The scope of work is set out in the remainder of this section and detailed more fully in the final confidential project report (Grey, 22-013 Confidential Project Report, 2022). The work breakdown structure main tasks were as follows:

3.1 WP 101 Project management

Objective: To deliver the project on time and on budget whilst ensuring all objectives are met.

Project management was carried out by AWS internal team with support in health & safety matters from Hydrosafe Ltd.

3.2 WP 102 Technical direction

Objective: To provide technical oversight of the project, including design review at critical points.

AWS formed a technical advisory group to assist with the technical oversight. This included independent sector experts with relevant expertise. This group of individuals, together with AWS management brought together some of the deepest experience and expertise available in the wave energy industry.

3.3 WP 201 Engineering design to tender

Objective: To prepare the engineering designs and procurement specifications necessary to allow procurement of the construction of the complete PSWD system in a manner which obtains value for money and reduces risk of time and cost over-run.

The engineering design and specification process was subcontracted to Quoceant Ltd. Unfortunately there was some programme slippage on the initial delivery of the designs, largely due to the re-working of the concept to re-locate the rolling seal. This meant that the FEED work carried out as part of the NWEC Stage 2 project could not be re-used. Notwithstanding, this stage was completed within 6 months to a point where AWS could request tenders for the construction of the Waveswing.

3.4 WP 301 Engineering design completion

Objective: To prepare the final engineering designs and manufacturing drawings to allow manufacture and construction of the full PSWD system.

Again this part of the project was subcontracted to Quoceant Ltd, while the detailed design of many of the sub-systems (e.g. hydraulics and electrics) were included within the construction and assembly contract (see 3.8).

3.5 WP 401 Simulation & model testing

Objective: To improve the existing numerical model to include pitch and roll degrees of freedom and to reflect the final design of the PSWD. Further to validate this model against previous model results, tank test data and if possible test data from the open-water trials of the PSWD.

This work had several phases, broadly split between numerical modelling and physical testing.

A new numerical model was created by K2M Consultants using the WEC-Sim platform. This model now gives AWS access to full 6 degree-of-freedom simulations, and is thus a useful design tool. The model was validated against both the previous 1 DoF model and against tank test data.

Both 1:20 scale (performance) and 1:40 scale (survival) tank tests were carried out at FloWave in Edinburgh. These provided additional data for validation of simulations, whilst also confirming that the revised seal configuration did not compromise the WEC power capture performance.

Further validation of the model is ongoing using results from open-water testing.

3.6 WP 402 Development and testing of rolling seal

Objective: To design, manufacture, test and supply the key rolling seal component for integration into the PSWD.

This work package was sub-contracted to Trelleborg who are a major manufacturer of seals and polymer components. This built on earlier work by AWS in identifying and testing suitable materials for flexible diaphragms and we were able to use virtually identical rubber and reinforcement compounds as we had previously tested. Note that previous tests include flex-fatigue testing to 16 million cycles.

Production of the seal presented challenges as it was necessary to cure the rubber in a single operation which required a large autoclave. Our seal was at the size limit for Trelleborg's facility. The work included development of the seal clamping arrangement and factory testing to 3.5 Bar pressure.

Once delivered to AWS, the seal was successfully installed in the Waveswing and has performed well in service. A photograph of the seal before removal from the production former is presented in Figure 3.

3.7 WP 403 Development and validation of PTO control

Objective: To develop the necessary control systems (hardware and software) to achieve the level of performance required of the PTO. Note that following a review of the PTO options it was decided to create a new PTO based on a combination of automotive motors and drives, and standard hydraulic components. This work package therefore necessarily increased in scope.

The development was successful, with a PTO being built which is capable of accurate real-time position control such as is necessary to allow efficient wave power absorption. The system was dry-tested initially without the floater being connected, and then further tuned following installation of the WEC in Scapa Flow. The relationship between demand and delivered position control can be seen in the lower graph in Figure 4 below.

Figure 3: Rolling seal on former in Trelleborg factory

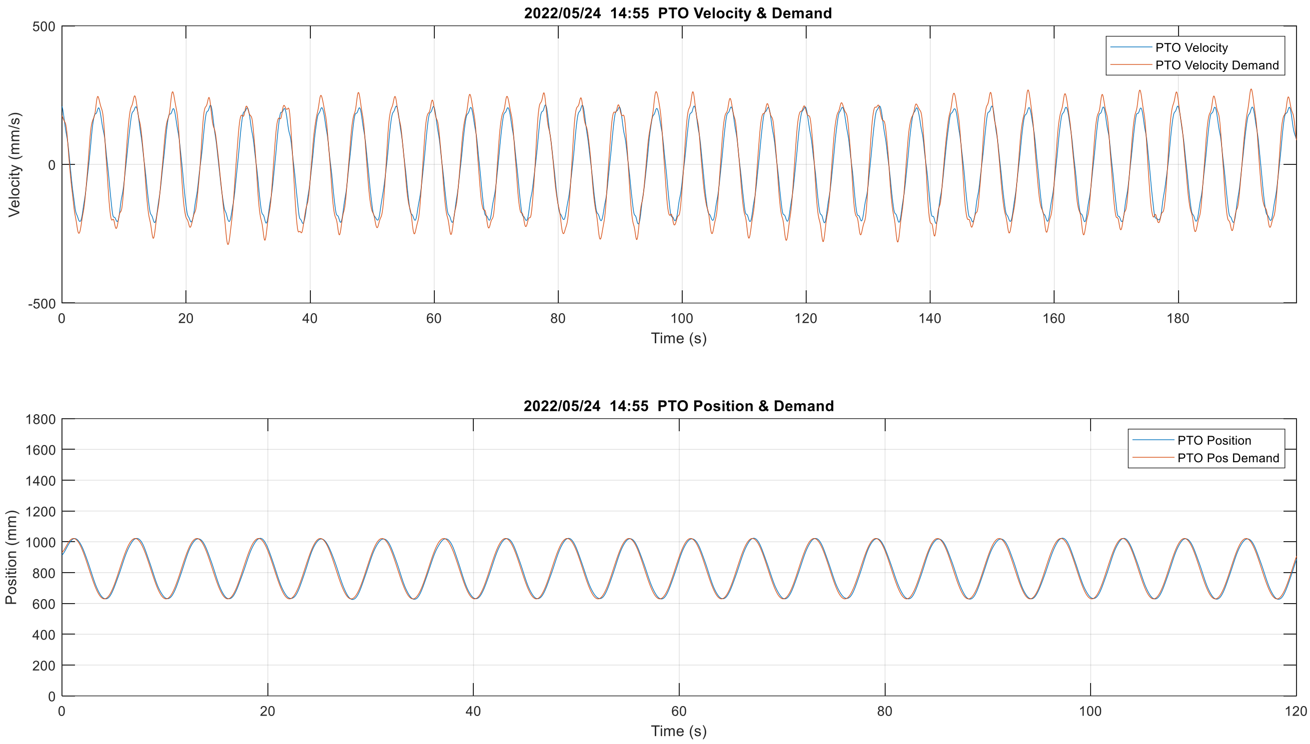

Figure 4: PTO control performance during a forced oscillation test at sea (6 second period)

3.8 WP 501 Fabrication and assembly of Waveswing

Objective: To build and assemble the complete Waveswing device.

The contract for the build and assembly of the Waveswing was awarded to Malin Group who have a large fabrication facility in Renfrew, Scotland. Work commenced in February 2020, but was almost immediately put on hold for 3 months due to the Coronavirus pandemic. Work resumed in July, however restricted working practices had impacts on both the fabrication work and on subcontract systems manufacture and supply.

The assembly work was largely complete by the end of June 2021, some 9 months after the original contract delivery date. Images from the fabrication process are shown in Figure 5 and subsystems are shown in Figure 6.

- Malin Group, Renfrew


Figure 5: Major fabricated components in Malin's factory in Renfrew

Figure 6: Key internal sub-systems

3.9 WP 601 Device commissioning & dry testing

Objective: To complete the commissioning of all sub-systems and then as far as possible to test these in factory conditions. For example, pumps and motors were characterised, times taken to achieve pressure changes with the environmental control system were measured, and the pull-down winch system was characterised.

This work was undertaken partly at the fabrication facility in Renfrew and then completed at a yard in Muir of Ord. The reason for the split was to avoid any disruption to the commissioning programme as a result of the COP26 summit in Glasgow in November 2021.

3.10 WP 602 Cyclic testing

Objective: To carry out multiple cyclic testing of the rolling seal by moving the floater. This was a key de-risking activity prior to deploying the PSWD at sea.

Cyclic testing presented a challenge due to the fact that on dry land the floater has considerable weight which must be supported by the PTO, whereas at sea the floater is self-supporting. It was therefore necessary to use a mobile crane to assist with cyclic testing (see Figure 7) and this limited the duration of tests due to the cost of crane hire. Nonetheless, the tests provided good confidence in the performance of both the PTO and the rolling seal.

Figure 7: Cyclic testing of Waveswing at crane yard in Muir of Ord

3.11 WP 603 ORR

Objective: To complete an operational readiness review, including a review of all test and commissioning activities, readiness of marine operations resources, emergency planning, consents and licenses, insurances and all other operational requirements ahead of committing to deployment.

This review was competed in two parts with final sign-off being achieved in mid-January 2022.

3.12 WP 701 Anchor block installation / adaptation

The anchor was originally intended to be the adaptation of a single concrete anchor block owned by EMEC, but after reviewing this in more detail a decision was taken to pursue the design and fabrication of a new anchor frame to suit available dense concrete anchor blocks.

The anchor frame is shown in Figure 8 and the dense concrete blocks that fit the bays on the frame are shown in Figure 9.

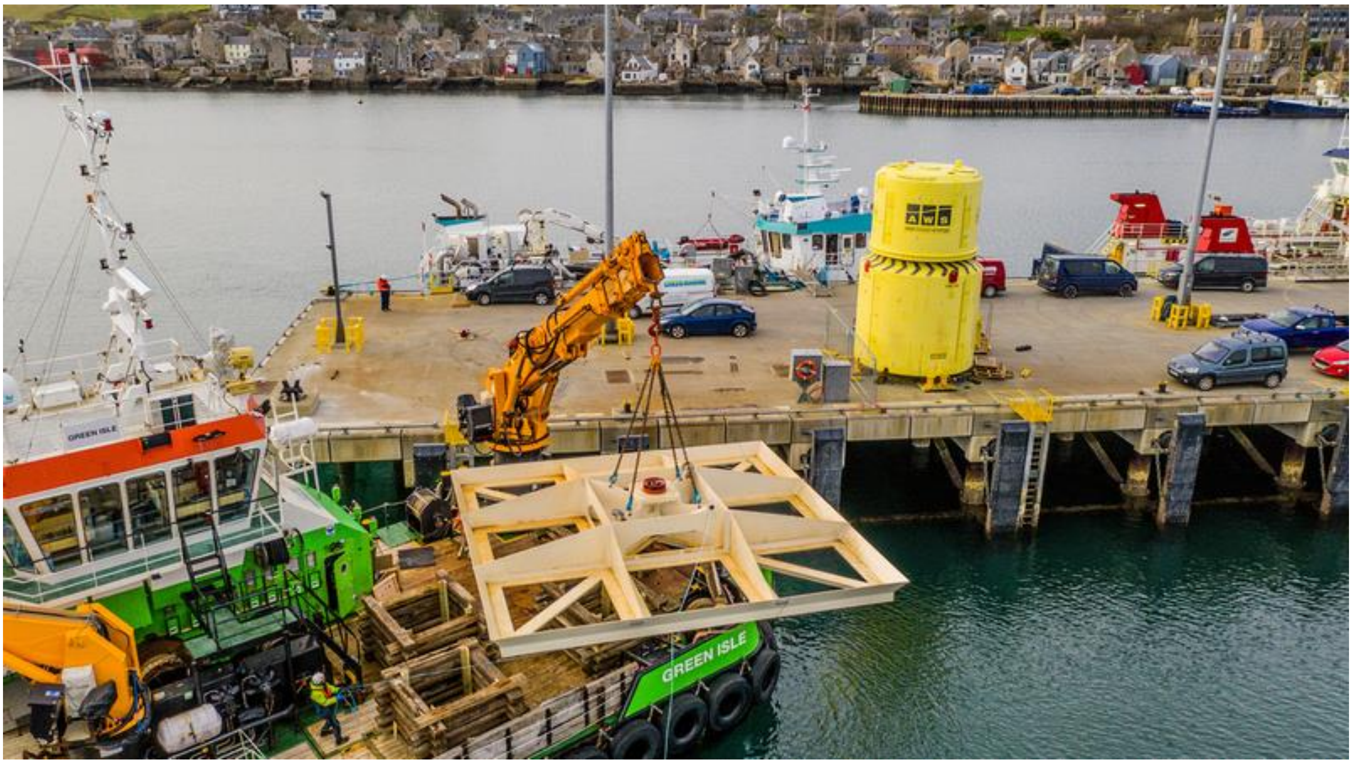

Figure 8: Gravity-base anchor frame

Figure 9: Dense concrete blocks to ballast anchor frame. Each block weighs 22t

3.13 WP 801 Site preparation & infrastructure

Objective: To obtain all consents necessary for deployment of the WEC and to make the necessary arrangements with EMEC, including configuration of the test-support buoy and microgrid.

The work was carried out in good time by the AWS team working in conjunction with EMEC. AWS were very grateful to secure the support of the OceanDEMO programme in relation to the berth at EMEC.

3.14 WP 901 Transport & initial deployment

Objective: To transport all the component parts of the PSWD project to Orkney, to assemble these and to deploy at the test site. This work package also included lifting and handling trials and tow trials.

Originally it was proposed that the WEC would be towed from the construction site to Orkney for onward deployment. However on investigation it was found that both the cost and the risk of this operation were higher than for road transport for a WEC with the dimensions of the Stage 3 device.

The WEC was therefore transported by road, initially to Muir of Ord near Inverness for ongoing testing, and then onward to Aberdeen and by ferry to Kirkwall. It was found that the road transport option was trouble-free, however, experience from road transport and ferry reiterated the importance of needing to be aware of limiting dimensions for transport early in the design stage so that any design decisions can be made with this in mind. As it was, there was 50mm clearance around the WEC on the ferry.

Figure 10: Waveswing during road transport

The Waveswing finally arrived in Orkney at the end of January 2022, however a run of particularly poor weather prevented a deployment attempt until 17 March 2022. Unfortunately the first deployment attempt had to be aborted due to an internal system failure. The WEC was finally deployed for the first time on 27 March 2022.

Figure 11: Waveswing under tow alongside the Green Isle multicat work-boat

Figure 12: Waveswing during submergence operation

3.15 WP 1001 Site commissioning & testing

Objective: To commission the WEC on site including commissioning all of the remote control, data logging and monitoring functions and then to carry out a test programme.

This work was carried out in several stages, beginning with the commissioning of systems during dry testing and moving on to commissioning of the remote communications and SCADA system whilst the WEC was on the quayside. Finally, systems were progressively commissioned with the Waveswing deployed on site. During this stage, systems were operated in 'manual' mode as we learned how to control the WEC. Once sequences were confirmed as being correct we moved on to considering how to automate those.

Testing has progressed with test objectives being much wider than just measuring power performance. In particular the tests have included trialling techniques for towing, handling and installation, together with testing of the internal systems. The most important part of the test programme has been the characterisation of the WEC and the improvement and validation of the numerical models for the device.

Testing was concluded on 2 November 2022 and the WEC was subsequently removed from the water. In summary, the tests have established:

- The pressure response of the device as the floater displacement is varied. This was a major unknown in the device performance and resolving this allows us to model the device response with increased confidence (see Figure 13).
- The hydrostatic spring characteristic of the device. Whilst the hydrostatic spring is well known for surface piercing devices, the spring response of the Waveswing had not been validated. We have found that the spring rate is significantly less than for an equivalent point absorber, resulting in a significantly higher response to wave action.

- Testing was carried out to attempt to establish the hydrodynamic added mass and radiation damping. It was found that establishing these parameters in open-water testing was challenging due to the un-controlled nature of the site conditions and the dominance of wave forces in the measured data. AWS would not recommend relying on open-water testing for derivation of these parameters, instead establishing them using radiation-diffraction solver programmes validated with tank testing.
- Power absorption was measured in a range of sea-states and was found to be in line with or slightly higher than that predicted by the numerical model developed in Stage 2, which despite its deficiencies compared to the K2M model, offers a closer representation of the device behaviour in the wave environment of Scapa Flow. An example power output plot is shown in Figure 14

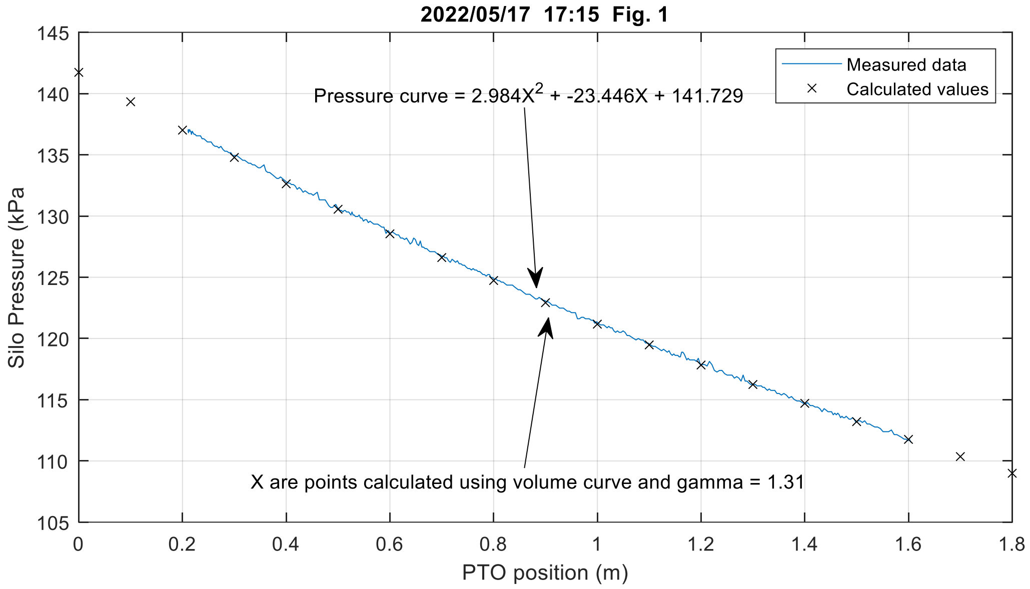

Figure 13: Validation of pressure-displacement relationship

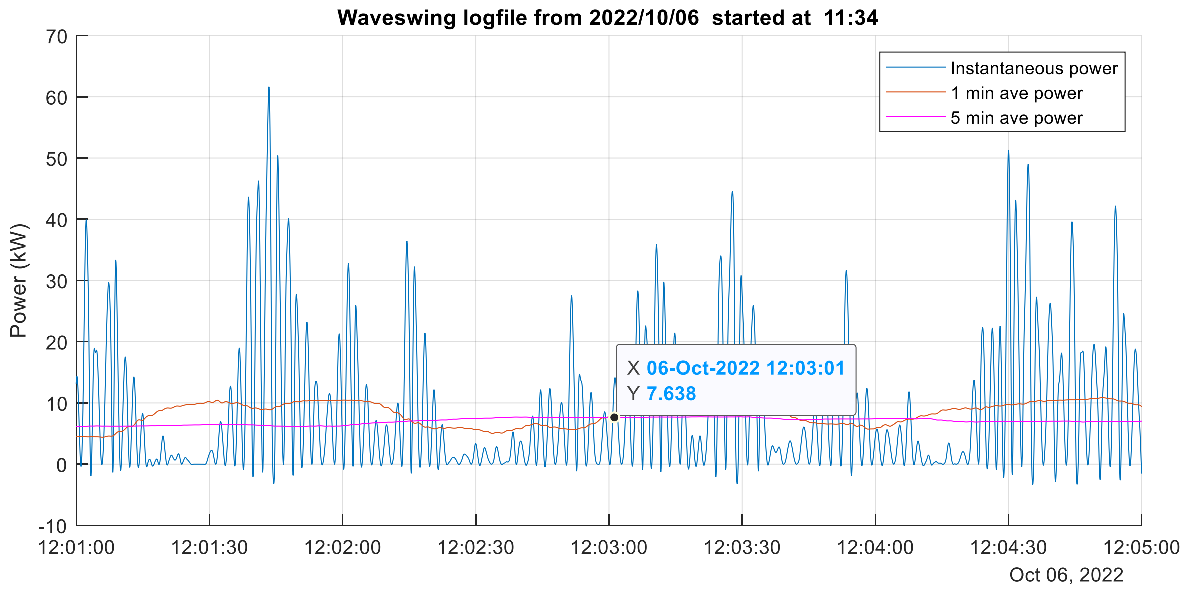

Figure 14: Example extract of power performance plot in moderate waves (Hs = 1.6m)

3.16 WP 1101 Decommissioning

Objective: To remove the WEC from site and then to decommission all of the component parts of the PSWD project.

At the time of writing the WEC has been removed from site and is in the process of being moved to a yard in Stromness for storage pending a re-deployment at a more energetic site for extended testing of the seal. Decommissioning of the anchor has due to be completed imminently.

3.17 WP 1201 Business development & commercialisation

Objective: To investigate potential market applications and possible early-adopters for the Waveswing technology and to develop a commercialisation plan for the technology.

During the project period AWS engaged with a number of potential end-users and commissioned independent work by a specialist adviser. This work by its nature is confidential and hence not repeated herein. A key outcome however is that as a result of this work, AWS believes that the key market for wave power is in utility-scale power production, and that this can be achieved using multi-absorber platforms which have the potential to be rated at several MW. AWS also believes that there is a significant opportunity for co-locating wave power generators with the recently announced ScotWind offshore wind farms.

A possible conceptual arrangement for a multi-absorber platform using 21 x 500kW Waveswing absorbers is shown in Figure 15.

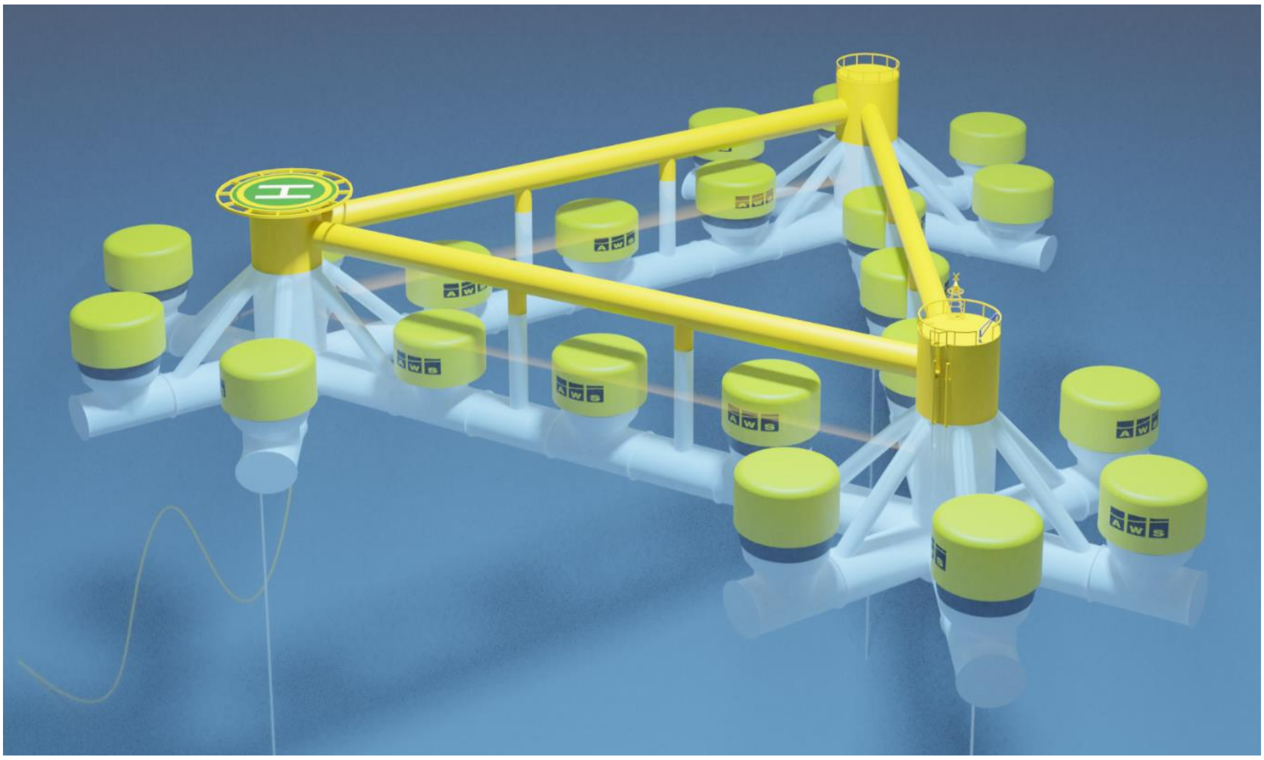

Figure 15: A 10.5MW capacity multi-absorber wave energy platform (MAWP) based on Waveswing modules

3.18 WP 1301 Planning & final reporting

Objective: To develop an onward technical development plan for the technology and to report on the project and disseminate lessons learned.

This work has included production of both a technology development plan and a business plan to support the further development and roll-out of the Waveswing multi-absorber technology. These documents will be made available to interested parties under a non-disclosure agreement.

3.19 WP NW01 – Offshore deployment initial feasibility

The objective of this work package was to investigate the feasibility of deploying the WEC at EMEC's Billia Croo test site, to establish any engineering or other requirements for such a deployment and also to investigate the feasibility of accessing the WEC at sea for minor maintenance.

The work concluded that it would be feasible to deploy the WEC at Billia Croo between March and September (inclusive) subject to some minor modifications to internal systems and the survival strategy.

The work also concluded that it was not possible to safely access the WEC for maintenance whilst deployed at sea.

3.20 WP NW02 – Offshore deployment final feasibility, planning & procurement

The objective of this work package was to confirm the outline feasibility conclusions from NW01 and to carry out the planning and pre-procurement work in order that the offshore test could be implemented at Billia Croo if required.

This was completed, however after a review it was concluded that there was insufficient time or budget available to allow the deployment at Billia Croo during NWEC. Notwithstanding, the work was valuable as it confirmed that the Waveswing is suitable for extended testing at an exposed offshore site and provided AWS with the design and cost information to allow planning of such an extended test.

3.21 WP NW03 – Extended testing at Scapa Flow

The objective of this work package was to carry out further testing of the WEC at the Scapa Flow site beyond the end of the NWEC3 period. This was completed, with 14 weeks of additional testing being achieved prior to the final recovery of the WEC in November 2022.

4 Project Achievements

4.1 Main achievements

Overall, the team consider the Stage 3 project to have been a major success in the development, demonstration and de-risking of the Waveswing technology. The key objectives as set out in §1.2 were met and progress was made well beyond targets and expectations. In particular the following represented considerable success points:

1. Re-configuring the design concept of the WEC to use a single sealed chamber without impact on power performance, whilst eliminating significant risk and cost in the system;

2. Producing and validating a new numerical model for the WEC which is capable of modelling all 6 degrees of freedom and predicting both power performance and structural loading under survival conditions;
3. Engineering from scratch a PTO system which has proved itself capable of meeting the functional requirements of the PSWD, including peak force capability and controllability and demonstrating the use of low-cost automotive components in this application;
4. Developing, installing and demonstrating the rolling seal, thus addressing a significant perceived technical challenge;
5. Completing the detailed design, specification and procurement of the complete WEC system in a way that ensured that requirements were fully met whilst the project budget was not exceeded;
6. Completing the manufacture, assembly and commissioning of a complete Waveswing device capable of deployment in open-water real-world conditions. This included solving numerous integration challenges between the multiple components and sub-systems;
7. Demonstrating the road-transport, offload, tow and deployment of the complete PSWD system, thus confirming that wave power systems of a scale capable of <50kW continuous power in open ocean can be compact and transportable;
8. Fine-tuning marine operations such that a complete launch, tow and deployment cycle can be completed in under 8 hours, thus reducing the cost of each deployment / recovery to 1 vessel-day;
9. Demonstrating the operation of the self-installation and tidal compensation system;
10. Demonstrating and verifying the behaviour of the internal air-spring and confirming agreement with numerical modelling to within 1%;
11. Demonstration of PTO control to achieve excellent alignment between force and velocity, thus maximising power absorption, even in small, short-period waves;
12. Demonstrating the operation of the rolling seal at sea over multiple cycles;
13. Completing the project including the full build and in excess of 20 major lifting, handling and marine operations without injury or health and safety incident;
14. Developing procedures for confined space working to allow access to the Waveswing ashore for maintenance purposes;
15. Gaining significant operational experience and understanding in relation to the Waveswing technology, thus allowing refinement of everything from control sequencing to marine operations and providing a solid basis for future development of the technology;
16. Through operations, gaining a thorough understanding of the minimum costs and potential issues in relation to deployment of small single WECs for remoter power applications;
17. Through market engagement, gaining an understanding of the requirements for future WEC development if wave power is to make a significant contribution to net-zero targets, and through this work deriving concepts for utility-scale multi-absorber platforms capable of competitive LCOE;

These achievements together represent a significant advancement in the Waveswing technology. AWS considers that on the one hand, significant progress has been made in addressing the key risks in the Waveswing core technology, thereby allowing single Waveswing units to be designed and supplied to remote power applications, whilst on the other hand a development path leading to genuine utility-scale capability has been identified.

4.2 Lessons learned

In terms of lessons learned, these were many but included the following main points;

Design process and timescales

During Stage 2 of the NWEC programme we noted the following lessons in relation to design processes:

- *"The project set an ambitious work programme and completion within the time and budget available was challenging. This put pressure on some of the design processes and as a result some inconsistencies crept in. Whilst these were minor in nature, they nonetheless reflected the importance of rigorous systems engineering procedures and design process control;*
- *It is the nature of R & D that design iterations will be required. The tight project timescale and linear programme did not allow for design iterations (e.g. after the CDR) and hence some aspects of the design were not fully closed out as we would have wished;"*

Unfortunately, these issues recurred within the defined project timescale and budget for Stage 3. This put additional pressure on the project team, and in the absence of tight contract control could have led to significant cost escalation. We again recognise that some key lessons are:

- Sufficient time and budget must be allowed for the design process. This should allow additional contingency time both before and after key design reviews. Furthermore, the time required to produce specifications of sufficient quality, to ensure that contractors actually supply what is required, should not be underestimated;
- Involvement of key contractors, including in particular the marine operations contractor in the development of the design could lead to design improvements and cost reductions. This however requires sufficient time in the programme to carry out a contractor selection process (which, in this case, must be compliant with public procurement rules) ahead of design finalisation;
- It is noted that the Construction (Design and Management) Regulations 2015 require clients to allow sufficient time in the programme to ensure that health and safety is adequately considered during the design process. AWS worked with WES to ensure this requirement was met in the context of the defined timescales in Stage 3..

Overall, it is the view of AWS that significantly more time and budget must be allowed during the detailed design and specification process. AWS would recommend a minimum of 12 months from project start to issuing of contracts for manufacturing to commence. If the FEED is not fully developed at project start, then a further 6 months should be allowed.

Contracting strategy and construction process

AWS adopted a strategy of seeking a single contractor for the construction, assembly and pre-commissioning of the Waveswing. This approach was chosen in order to minimise contractual interfaces and to reduce the need for significant co-ordination between contractors and suppliers of equipment.

The approach worked reasonably well, however in future AWS would invest significantly more time in ensuring that the main contractor fully understands the project scope and has suitably skilled and experienced staff. It is also important to ensure that any sub-contractors also have a full understanding of their scope and that the requirements set out in the specifications are there for a purpose and must be adhered to.

It is necessary to recognise that there will be uncertainty in any prototype construction project and it is important to ensure that any manufacturing or installation contract includes fair mechanisms for compensation of the contractor when the unexpected happens.

Device performance

At the time of writing, AWS do not have sufficient data to draw lessons from the device performance, other than to state that the performance was not adversely affected by the change in configuration to include the rolling seal.

Transportation

A key success in the project was the transport of the WEC from Glasgow to Muir of Ord and then onwards to Orkney. Road transport was established as a quick, low-risk and cost-effective method of transport, however other developers should be aware of size constraints for both bridge clearance and ferries. It is well worth considering transport early in the design process to ensure that the intended method is feasible.

A further lesson learned was that all lifting operations need to be considered during the design process to ensure that adequate lifting points are provided. This is a requirement of the Construction (Design and Management) regulations 2015, but it is worth re-stating here.

Marine operations

The marine operations were executed smoothly, however this was in large part due to using experienced people to plan them out and ensuring that a HIRA (Hazard Identification and Risk Assessment) was carried out by the installation team.

Lessons to be learned include that the importance of involving marine contractors early in the design process in order to ensure that the WEC has all of the features likely to be necessary to facilitate operations offshore. Again operational planning is a requirement of the CDM Regulations.

A further learning in relation to marine operations is that there is a minimum cost associated with a deployment / recovery operation for any WEC. Vessels, crew, equipment and fuel all have a market cost and minimum day-rates. Similar comments apply for quayside craneage. AWS developed a slick operation where a crane-in / out can be completed in 2 hours, and where an install / recovery of the WEC can be completed in 8 hours. Notwithstanding, the minimum cost achievable for these operations is around £35,000 (2022 prices). Costs may be higher in non-sheltered waters. Developers should bear this in mind when assessing LCOE for single WECs.

Overall

The Archimedes Waveswing technology is capable of manufacture and deployment at real-world scale, whilst the device response and performance is capable of being modelled accurately. The concept now offers the prospect of deployment in single-unit configuration to meet remote power needs, although it should be noted that as with all other WEC technologies, single deployments will carry a disproportionately high operation and maintenance cost.

The Archimedes Waveswing technology however is also capable of deployment in multi-absorber configuration which allows feasible on-site maintenance and consequently significantly lower levelized operating costs. With the base technology now proven and demonstrated, the next stage is to develop the multi-absorber platform for utility-scale power generation.

5 Summary of Performance against Target Outcome Metrics

5.1 Performance against target metrics

Overall performance against the target metrics set at the entry to the Stage 3 project was reasonable with the following specific metrics being achieved:

Affordability

Metric	Target	Result	Notes
Structural fabrication cost	£4,500/ton	£6,800/ton	Tender prices ranged from £6,000/ton to over £12,000/ton. Realistic targets for future should be in the range £8,000/ton including painting.
Assembly of sub-systems into Waveswing	£100,000	< £100K	Result not clear as costs included in supply of subsystems. Target appears achievable for future with modular design.
Commissioning cost	£65,000	£118,000	Significant increase due to poor design and management of integration by subcontractors. Target can be met in future with improved design.
First installation cost	£50,000	£68,330	Change to anchor design necessitated complex 3-day operation to install, thus increasing costs.
Recovery & re-installation cost	£30,000	£18,600	Operations refined to reduce ‘each-way’ marine ops to under 8 hours and £10K cost. Note that craneage was not allowed in original target and adds £8K each way to total costs at this scale.

Performance

Metric	Target	Result	Notes
Improvement in scale model performance	No detriment due to seal	n/a	The scale model performance remained unchanged from NWEC2.
Mechanical power capture in real-sea conditions		1-minute average > 11kW. Peaks >80kW.	Full range of conditions not available for testing but points measured exceeded numerical model predictions.
Operation of PTO velocity control		PTO velocity control generally within 5% of target.	Result depends on incoming sea-state. Stability limits on PTO limited gain possible and hence control in larger seas did not meet target. To be improved in future testing.
PTO conversion efficiency		n/a	With the change to the PTO from a subcontractor product to an experimental rig, measurement of PTO efficiency was not considered relevant.

Availability

Metric	Target	Result	Notes
Time to deploy WEC	12h	<8h	Successfully demonstrated
Time to recover WEC	12h	<8h	Successfully demonstrated
Time to access WEC for minor repair	12h	n/a	n/a It was decided not to be safe to access the WEC at sea.

Survivability

Metric	Target	Result	Notes
Time to enter survival mode	5 min	<4min.	Dependent on winch speed of 0.4m/min.
PTO end-stop events	Zero	Several	Due to PTO drive faults and incorrectly configured control (brakes) software
Fault-free operation of rolling seal	1 million cycles		Ongoing

Detailed evidence for the above is provided within the various project reports which whilst confidential may be released to interested parties under NDA following agreement with AWS Ocean Energy Ltd.

6 Recommendations for Further Work

This Stage 3 project resulted in the complete WEC being advanced to TRL 6, however noting that some sub-systems may be re-designed and hence will be at lower TRL until tested at operational scale.

As noted in 3.17, AWS considers that commercialisation of the Waveswing WEC should be by deployment on multi-absorber platforms. Accordingly, the next step in the development process will be the design and construction of an operational multi-WEC platform using Waveswing absorbers.

AWS suggests that a suitable demonstration unit could comprise 4 absorbers arranged around a central spar structure. This would allow the demonstration of:

- Construction of absorber modules at large scale (e.g. 8m diameter);
- Cost-effective local construction of the sub-structure;
- At-sea access and maintenance in an exposed location (e.g. EMEC, Billia Croo);
- Power absorption of multiple absorbers;
- Operation of a PTO of the design intended for commercial operation;
- Multi-cycle operation of the rolling seal;
- Benefits of services aggregation between absorbers and centralised control and electrical systems.

AWS is in the process of developing a detailed technology development plan to deliver this next phase of development.

7 Communications and Publicity Activity

During the course of the project the team has been focused on the technical aspects of the work. Accordingly, communications and public engagement has been relatively limited. Notwithstanding, AWS has carried out the following activities in relation to communications and public engagement:

- Re-development and updating of our website (2021 / 2022);
- Production of 'how it works' video for Waveswing;
- Production of two videos of project progress in Orkney;
- Project press releases;
- Participation in 2 annual WES conferences;
- Attendance at All Energy exhibition and conference (2019 and 2022)
- Presentation to Orkney Science Festival;
- Presentation to ETIP / OceanDEMO webinar;
- Several feature articles including FishFarmer magazine.

In addition, EMEC have produced an excellent video of the deployment process and have publicised the project through their channels.

8 Publicity Material

Please supply WES with at least one high resolution image of the device that may be used for publicising the project. Please also provide company logos for the lead contractor and subcontractors (high resolution) and any other supporting publicity material generated during the project (e.g. video files, posters, etc.).

Files should be uploaded to the Objective Connect milestone folder. Use the table below to summarise the publicity material.

Filename	Media Type	Description
AWS_full_logo	Jpg	AWS corporate logo
4cE.png	png	4cE corporate logo
Alfik.png	png	Alfik corporate logo
AWS.jpg	jpg	AWS corporate logo
EMEC.png	png	EMEC corporate logo
Green Marine.png	png	Green Marine corporate logo
Heddles.gif	gif	Heddles corporate logo
Hydrosafe.png	png	Hydrosafe corporate logo
Malin.jpg	jpg	Malin corporate logo
Orcades.jpg	jpg	Orcades corporate logo
Pelagic.png	png	Pelagic corporate logo
Quoceant.png	png	Quoceant corporate logo
Sequentec.png	png	Sequentec corporate logo
Stoddarts.png	png	Stoddarts corporate logo
Trelleborg.png	png	Trelleborg corporate logo
AWS_insideWec.jpg	Jpg	View of WEC internals looking up. Photo credit Colin Keldie.
AWS_wecAfloat.jpg	jpg	View of WEC on surface of Scapa Flow during deployment. Photo credit Colin Keldie.

9 Acknowledgement of support from OceanDEMO

The team is grateful for the financial support received from the Interreg North-West Europe OceanDEMO programme which met the costs of berth rental and services associated with the EMEC berth.