Archimedes Waveswing MK IV

WES Novel Wave Energy Converter
Stage 1 Project
Public Report

AWS Ocean Energy Ltd

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

This project set out to complete a full proof-of-concept and techno-economic feasibility study for a new variant of the Archimedes Waveswing™. This innovation, if feasible, is expected to deliver a significant advancement over the Waveswing™ MK II for which development was suspended in 2009 due to poor economic performance. In particular, the new arrangement was expected to remove significant costs from the mechanical and electrical ("M&E") sub-systems whilst also allowing the development of potentially smaller devices to allow an early route to market (competing with diesel in remote locations). The specific objectives of the project were:

- To advance the understanding of the Waveswing™ technology, including in particular the hydrodynamics of the new arrangement and to use this understanding to develop and validate advanced numerical models of the system;
- To demonstrate a novel and highly effective control strategy for stroke limited devices without the need for advanced knowledge of incoming waves or use of model predictive control;
- To confirm the energy capture potential for low-volume sub-sea wave energy converter ("WEC") devices and to demonstrate broad-banded responses across a range of sea-states;
- To create and validate a parametric techno-economic model and to use this tool to identify the optimal configuration for best economic performance and early demonstration of the Waveswing™ technology;
- To carry out sufficient concept engineering (including review of the significant work completed for the previous Waveswing™ variant prior to 2009) and from this to identify the technical challenges, concept solutions and technology development plan;
- To identify a development pathway, which can lead to a levelised cost of energy ("LCOE") of less than £150/MWh.

The project was successful in achieving all of these objectives and has resulted in a very significant advancement in the understanding of the Waveswing™ technology. The project has also resulted in the production of numerical models and tools which will both underpin the future development of the Waveswing™ technology and could be of value to the wider wave energy community.

The project team was led by AWS Ocean Energy Ltd who own the Waveswing™ intellectual property and who, with predecessors, have been developing the technology since 1998. Significant technical input was provided by Johannes Spinneken of Evergreen Innovations who developed all of the hydrodynamic and control theory and implemented the numerical models. Technical oversight and project management support was provided by John Fitzgerald (formerly of AWS) and Claire Cohen of Black & Veatch Ltd., whilst the concept engineering and a feasibility review was provided by Quoceant Ltd. Last but not least was the valuable design and build of the 1:20 scale model by 4c Engineering and 4c Design, respectively, and the excellent facilities, services and support of the FloWave test tank team.

1.2 Description of Project Technology

The Archimedes Waveswing™ is a submerged self-reacting point absorber driven by differential pressures caused by incident waves. In simple form the device is a submerged telescopic structure with a lower part tethered by a mooring and the upper part free to move vertically. The system is deployed in deep water with the clearance from device crown to mean water level of 3m at top of stroke. The system can be scaled from a few tens of kW to several hundred kW. Based on the outcomes of this project, the AWS team believes that 150 to 200 kW is an appropriate scale for first commercial devices and that the system can be scaled from there to several hundred kW per device.

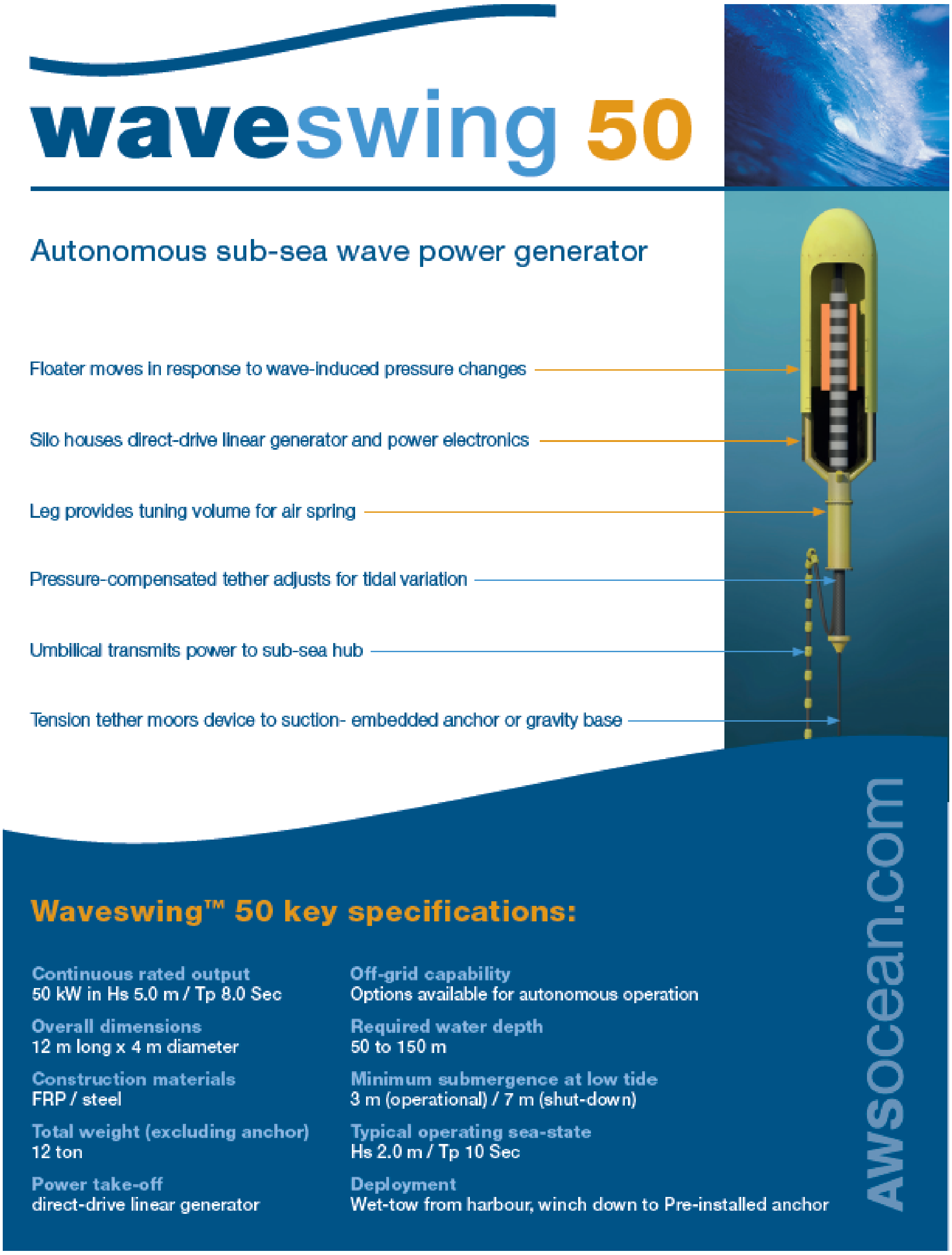

Figure 1: Overview of 50kW Waveswing used as baseline for project study work

The device comprises two large concentric cylinders arranged in telescopic fashion. The moving upper part, the Floater, is an inverted 'can' which provides the wave absorbing surface whilst the lower fixed part, the Silo, contains the power take-off ("PTO") and other equipment. The Silo is held on station by means of a tension tether connected to a suitable anchor, the design of which is dependent upon sea-bed conditions. The relative motion between the two parts drives a linear generator power take-off unit.

The Floater and the Silo together form two gas chambers. The inner chamber housing the PTO contains a partial vacuum whilst the outer chamber contains air at a pressure equal to the hydrostatic pressure of the free-surface of water in the gap between the Floater and the Silo. The combined forces acting on the Floater due to the two pressure chambers are arranged to balance the external hydrostatic forces at equilibrium. As the external pressure increases due to a passing wave crest, the Floater is driven downwards, thus reducing the down-force caused by the partial vacuum and increasing the up-force due to compression of the air in the Gap. The reverse happens under a wave trough. Through careful balancing of the Gap and Silo volumes, a 'soft' and tuneable spring is produced. Tuning is achieved by varying the volume of water within a reserve chamber, thus varying the compression ratio of the Gap volume. For shut-down or storm survival, water is released from the chamber, thus depressurising the Gap volume and causing the Floater to come to rest at bottom of stroke.

The Waveswing™ is both innovative and unique in that firstly, the spring constant of the device is decoupled from gravity and is significantly softer than that available to heaving buoys, and secondly, the device is entirely self-reacting, thus it neither relies on a heave plate nor bottom reaction to counteract PTO forces. These are key to reducing the costs of wave power for the following reasons:

1. The moving mass is significantly reduced, thus reducing cost and improving bandwidth;
2. The absorber is higher in the water-column, thus in the energetic part of the wave-field;
3. Performance is not dependent on negative spring introduced through the PTO which, whilst effective in increasing ACE[1] will result in very high PTO and anchoring costs and poor conversion due to large amounts of reactive power;
4. The absorber reacts to long-period waves even at small scale and is not simply a wave-follower. This provides significant improvements over heave-plate reacting devices;
5. The high amplitude of motion achieved through the positive feedback and tuneable response allows the use of high-efficiency power take-off such as a linear generator.

This project has demonstrated that these key features enable the Waveswing™ to achieve very significant improvements in economic performance over other heaving-buoy type point absorber devices. Indeed, with the highly efficient use of participating volume, the Waveswing™ has potential

[1] "ACE" is a metric developed by the US Department of Energy for use in the Wave Energy Prize and is effectively a measure of effective 'capture width' of the WEC per unit cost of the structural components [1].

to exceed the economic performance of any other known concept. The Waveswing™ can be deployed in dense arrays to achieve significant farm ratings with excellent LCOE performance.

1.3 Scope of Work

With the ultimate aim of providing a full Phase 1 proof-of-concept investigation of a novel and innovative wave energy converter, the work was structured as follows:

A. **Design development**. Before commencing any detailed numerical simulations, mathematical modelling, physical model testing or concept engineering, it is essential to define the key device characteristics and functions. This specifically concerned the specification of a Basis of Design ("BoD"), which ensured compatibility between the various project tasks. The BoD includes key device dimensions (structure diameter, length and submergence depth) as well as anticipated power production ratings and power-take-off capabilities. The Waveswing™ BoD was subject to change as the project evolved, with all changes clearly documented and reasoned. The BoD evolution principally documents the maturing of the technology at the highest level.

B. **Hydrodynamic analysis**. The Waveswing™ wave energy converter produces electrical energy by interacting with the incoming water waves. The power conversion chain from wave energy to electrical energy entails a number of conversion stages, including both mechanical and electrical components. A thorough hydrodynamic analysis defined the fundamental interplay between the incoming waves (hydro) and the motion response of the Waveswing™ (dynamics). This step essentially defined the underlying "equation of motion" upon which all subsequent analysis and modelling was built.

C. **Numerical modelling**. If considered in isolation, each of the fundamental Waveswing™ functions (hydrodynamics, structural constraints, electrical generator performance, mooring system, control system) is relatively easily understood. However, the true technological advance lies in how these various functions are coupled in the most effective way. To establish the optimum Waveswing™ operation, the project team designed an advanced numerical device model.

D. **Physical wave tank testing**. While numerical models are undoubtedly very powerful and cost efficient, they must be validated against experimental data. A high-fidelity model of the Waveswing™ device was constructed at scale 1:20, replicating all key device functions including the complete power conversion chain. This model was tested in one of the world's most advanced laboratories, the FloWave TT basin.

E. **Simulation and optimisation**. The combination of the above tasks provided a fully validated numerical model of the Waveswing™ technology. This model was adopted to establish key performance indicators such as power conversion performance in realistic sea states as well as device loading and survivability.

F. **Concept engineering**. The concept engineering stage provided the essential step from functional performance (above steps) to realistic device implementation. This step entailed a detailed analysis of load cases, physical arrangement of the key functional components, installation procedures, and maintainability. The concept engineering also served the purpose of defining the cost of device construction, operation and maintenance.

G. **Parametric cost modelling**. Informed by the combined evidence of the above steps, the parametric cost modelling set out to establish the most optimum device configuration from an economic perspective. This was achieved by developing a simplified device model, calibrated against the detailed numerical and physical model test data, and also informed by the cost drivers established via the concept engineering phase.

H. **Lessons Learned Public report.** The principal goal of the Waveswing™ development work is to provide clean and cost effective renewable energy. This lessons-learned report was commissioned to convey the team's key findings, and to provide a realistic and transparent assessment of the state-of-the-art in wave energy production.

This work was completed over a 10 month period beginning in March 2016 and has resulted in very significant achievements as noted below.

1.4 Project Achievements

Section 1.3 outlined the scope of work and key project tasks. In presenting the project achievements, it is essential to highlight that these tasks cannot be considered in isolation. Instead, each distinct advance is first noted irrespective of how this advance was achieved, and then tied to the individual work items as appropriate.

The project commenced with the hypothesis that the Waveswing™ device can provide a step-changing technology advance. To prove this hypothesis, the aforementioned scope of work included mathematical modelling, numerical simulations, physical wave tank testing and economic analysis. Considered in their totality, these individual tasks have established a rigorous case for one of the most advanced wave energy technologies available today; the specific advances achieved being detailed as follows:

A. **Device operation proof-of-concept.** The power conversion chain is the heart of any wave energy converter, and any novel concept must demonstrate significant advantages over existing concepts. The Waveswing™ device introduces a highly innovative and previously unproven way of coupling the structure's response to the incoming waves, using a hydrostatic gearing feature that enables large motions even in relatively modest sea states. This gearing feature is then combined with a sophisticated control strategy ensuring that the maximum amount of energy is extracted from *each* oscillation cycle. The project has successfully demonstrated that

   a. The hydrostatic gearing principle is both effective and robust;

   b. The Waveswing™ device has an excellent excitation force characteristic and responds to a broad range of wave frequencies. The device operation remains effective even in very long waves;

   c. The device control can be implemented in a way that delivers electrical power across a very wide range of sea state conditions. The control strategy developed is fully autonomous and does not require instantaneous (wave-by-wave) tuning or prediction;

d. The Waveswing™ operation was confirmed via a series of physical model tests at scale 1:20;

e. An accurate numerical device model is now available to support and guide future development efforts.

B. **Cost modelling and concept engineering**. With the fundamental device operation proven, it is essential to demonstrate that the concept is feasible from both an engineering and economic perspective. Indeed, these two aspects are closely linked, with any implementation change directly affecting costs. This project has carefully considered the linkage between engineering and economics, establishing that:

a. The economic optimum for the Waveswing™ technology occurs for an 8m diameter device with a 3m stroke. The relatively large diameter delivers high exposure to incident wave forces which drive the operation of the device. A stroke of 3m is sufficient to capture the majority of the available wave energy at minimum structural cost. Despite these modest dimensions, the team is confident that such a device could be rated at up to 210 kW;

b. The modelling work and concept engineering work has succeeded in capturing a detailed understanding of the PTO's technical requirements. The modelling capability is capable of managing the interdependency between PTO capability, the operating envelope, energy capture as well as survivability and structural costs. The work has highlighted that the use of a directly-driven linear generator PTO, is potentially problematic under the very largest waves due to the limited force capability that such machines have. The economically optimal PTO is rated for a wave-height in the region of 2.75m for an Orkney resource. However, even imposing an operating wave-height limit of 4.75m Hs, the largest wave could well exceed 8m in height. This will overcome the PTO force limit and result in significant end-stop impacts that would not be survivable by the structure. Doubling (say) the PTO capacity would result in only around 7% increase in energy capture, whilst the worst end-stop events would still occur. The result is that an additional braking system is required with a peak power dissipation capability at least as large as the PTO. This calls into question the strategy of using a directly-driven linear generator and suggests that other solutions with higher peak force capability may be more suitable. This result is likely to apply across many classes of WEC, not just for the Waveswing™. Notwithstanding, it is still considered feasible to develop an affordable PTO system that meets the functional requirements;

c. A key feature of the Waveswing is that it is wholly submerged and has a soft hydrostatic spring. The soft spring, whilst essential to the highly efficient power capture of the Waveswing™, does require a certain volume of air to be contained within the device. This in turn results in high uplift forces on the moorings due to the buoyancy. Economic solutions for anchoring are offered by suction-embedded plate anchors. However, these are only suitable for certain sea-bed conditions. Work in 2008 identified a number of feasible anchor options and showed that costs are affordable, particularly in multi-unit farms where the cost of mobilising sub-sea installation equipment can be amortised across many devices. Affordable anchoring however remains a challenge for prototype devices;

d. A further feature of the Waveswing is scale-ability where devices are technically feasible from a few 10s of kW to several hundred kW. An attractive commercialisation strategy is to start with small devices and sell into niche markets meeting offshore and isolated power needs where the existing supply is expensive diesel. The study, however, identified that the fixed costs associated with electrical infrastructure mitigate against small devices and drive the LCOE up to an unacceptable rate. Work on economic systems would benefit the whole of the wave energy community and will be essential if the start-small strategy is to be successful.

Overall, the concept engineering showed the Waveswing™ to be feasible from an engineering perspective. This is perhaps not surprising as AWS had a team of 10 working on the front-end engineering design for the previous variant for 4 years and the majority of the sub-systems remain as previously conceived. In particular however, a novel arrangement for the main bearings was identified during the concept engineering and this has allowed structural costs to be reduced further and has improved load-paths and hence fatigue resistance and survivability.

C. Pathway to LCOE below £150/MWh

The parametric costing exercise proved valuable and produced some results that surprised the team. Previous modelling seemed to indicate that economics tended to improve as device size was reduced and that the optimal aspect ratio (diameter to stroke ratio) was around 1:1. The new results obtained showed that economics improve as the device size increases and that the optimum aspect ratio decreases as the diameter increases. The general results obtained were as follows:

a. With only modest learning rates, a viable pathway to a LCOE of £150/MWh is demonstrated;

b. Small devices, whilst maintaining the structural efficiency, are penalised by the high fixed costs of electrical connection equipment, installation and general project costs. Devices of around 200kW or more are required for these costs to be adequately distributed to allow acceptable LCOE;

c. Operation and maintenance (O & M) costs form a very significant part of the total LCOE, particularly for smaller devices where O & M accounts for in excess of 60% of the LCOE;

One observation from completing the study was that the parametric modelling and concept engineering are interdependent. A full optimisation process will require several iterations of concept engineering to allow cost definition, and then further adjustment of the parametric model.

1.5 Summary of Performance against Target Outcome Metrics

The project has demonstrated that the Waveswing™ has the potential to perform very well in terms of the target metrics for a commercially successful WEC. In particular, the project has demonstrated:

- Potential to achieve a LCOE for an optimised device of below £150/MWh once total installed capacity has reached around 1GW assuming only modest learning rates. Step-changes in technology (e.g. in cost-effective anchoring and power take-off technologies) could result in this cost level being achieved earlier. For a first demonstration farm using prototype costs and excluding any step-changes the LCOE remains high (in the region of £600/MWh). However, this cost is expected to reduce rapidly for the first few MW;
- The volumetric performance of the Waveswing™ is excellent with average annual energy yield of around 8.3MWh per m^3 of swept volume in a West Orkney resource. This is around [60%] of the theoretical maximum for a stroke-constrained point-absorber in this resource;
- The concept engineering review confirmed feasible maintenance strategies for the device as a whole and noted that the low complexity and small number of sub-systems is likely to result in high reliability. The device therefore has potential to reach availability targets approaching or even exceeding 90%;
- A key advantage of the Waveswing™ technology is the sub-sea location which enables the device to avoid significant storm loading. Analysis of the new variant has built in previous detailed research on survivability and has confirmed that the new device is likely to have a high survivability rating.

Overall therefore, whilst initial economic targets of reaching an un-supported early commercial market (e.g. direct competition with diesel power in remote locations) remains difficult to achieve, the longer-term potential of the technology to meet the target metrics for commercial power production have definitely been confirmed by the project.

1.6 Communications and Publicity Activity

During the course of the project, AWS were involved in the Wave Energy Prize competition run by the US Department of Energy. This resulted in a constant stream of publicity by way of updates on the prize website www.waveenergyprize.org. As part of this programme, AWS participated in two technology showcase events. The first was held as part of the National Hydropower Association annual conference in April 2016. The second was as part of the wave energy prize finalists' technology showcase in November 2016.

In addition, the Waveswing project has featured in a number of online renewable energy trade publications and will feature in a full article in the I.Mech.E journal in the coming months. It is expected that the results of the project will be further disseminated at events such as the International Conference on Ocean Energy and the European Wave and Tidal Energy Conference.

Finally, the AWS Ocean Energy website www.awsocean.com has recently been updated to feature the revised Waveswing design. This includes links to videos of the device during testing at FlowWave TT.

1.7 Recommendations for Further Work

Whilst the project has undoubtedly confirmed the feasibility and potential of the Waveswing™ technology, there does of course remain significant work to do to realise a system which meets commercial requirements. Development work falls into 5 categories, namely:

1. Further detailed study work to refine sub-system options upon which detailed design can be carried out (for example final selection of the PTO system);
2. Sub-system level technology qualification activities to reduce technical uncertainty and risk (for example bench-testing of novel components or materials);
3. Improvements in simulation and further experimental testing to increase confidence in energy yield performance, together with more detailed engineering design to improve accuracy in capital and operating costs. Together these activities will improve confidence in LCOE estimates and underpin the business case for continued investment in technology development;
4. Research and innovation activities which can result in a step-change in performance either through improved energy yield or through reduced cost;
5. Full prototyping and demonstration activities which advance the complete system towards commercial maturity and achieve full system qualification and certification.

The first three activities are likely to be undertaken as part of a Stage 2 investigation project, whilst the research and innovation activities may be undertaken in parallel or as part of other WES funded projects. The demonstration activities will be appropriate to Stage 3 and 4 projects.

The key activities anticipated for a Waveswing™ Stage 2 project will be as follows:

A. Experimental work

- Conduct further tank testing to confirm the performance of the optimal configuration 8m x 3m Waveswing and further validate the numerical performance model and advanced control strategies;
- Conduct tank testing to confirm structural loads under both operational and survival conditions in order to validate simulations and provide a basis for engineering design;
- Conduct bench testing of a partial-scale model of the rolling vacuum seal to provide proof of concept, validate finite-element analysis and begin to build confidence in life-cycle performance and durability;
- Conduct bench testing of a partial-scale model of the tidal compensation tether to build confidence in the life-cycle performance and durability;

B. Engineering design and economic modelling

- Conduct an engineering design study using outputs from simulation work in order to identify the optimum PTO solution for the Waveswing™ device;
- Carry out a FEED study for a full-scale device to confirm engineering solutions and increase confidence in costs, reliability and maintainability;
- Conduct a detailed LCOE study using supplier and operations contractor cost data and use Monte-Carlo analysis to establish the confidence levels in future energy costs;
- Carry out further development of the control system to ensure most effective device operation;
- Consider options for reducing anchoring loads and for provision of cost-effective anchoring solutions;

C. Preparation for subsequent stages

- Conduct a full FEED study for a partial-scale prototype device and prepare a project plan and budget.

It is important that the next steps in the development of the Waveswing are focussed on technology risk reduction and accordingly, the methodologies recommended in DNV-RP-A203 will be applied such that the complete system can progress through the various qualification stages. The focus on confirmation of the full-scale economics using rigorous engineering design and costing together with validated performance simulations will ensure that a high technology performance level or "TPL" [2] will be achieved prior to significant investment in at-sea hardware testing.