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Technology Description and Status
Waveswing™

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Contents

Figures, Tables & Appendices

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References

Doc Ref	Title	Author(s)	Issue / date
15-001r5	AWS Wave Power Development Experience	S. Grey et. al.	11/02/2016
15-012r3	Report on LCOE Sensitivity Modelling	S. Grey	11/02/2016
[R1]	WEC Technology Readiness and Performance Matrix – finding the best research technology development trajectory; International conference on Ocean Energy, 4th International Conference on Ocean Energy, Dublin	J. Weber et. al.	17/10/2012

Nomenclature & abbreviations

Name or acronym	Explanation
AWS	Archimedes Waveswing
AWS Ocean	AWS Ocean Energy Ltd
DNV	Det Norske Veritas
EMEC	European Marine Energy Centre
FEED	Front end engineering design
FRP	Fibre-reinforced plastic
HMRC Cork	Hydraulics and Maritime Research Centre, Cork
IAMS	Intelligent active mooring system
LCOE	Levelised cost of energy
M & E	Mechanical and electrical
Pilot plant	The 690kW AWS plant deployed off Portugal in 2004
PMG	Permanent magnet generator
PTO	Power take-off
TPL	Technology performance level
TRL	Technology readiness level
WEC	Wave energy converter
WES	Wave Energy Scotland Limited

1 General

1.1 Background

This document has been produced in response to a brief by Wave Energy Scotland (“WES”) to provide a report on the technology status of the Archimedes Waveswing™ wave energy device.

This report is one of a suite of reports provided to WES and the reader is recommended to read AWS Ocean report 15-001 *AWS Wave Power Development Experience* to further understand the background to the development of the Archimedes Waveswing™ technology.

1.2 Purpose of the report

The purpose of this report is to provide a description of the current design for the Waveswing™ technology (now known as Waveswing™ MK IV) and to provide a TRL assessment of the major sub-systems, together with an assessment of AWS Ocean Energy’s confidence of achieving TRL 9 for that system. The report also provides an assessment of the overall TPL of the system.

This information is intended to provide WES with a snap-shot of the current state-of-the-art in relation to the Waveswing™ technology.

1.3 Structure of this report

This report is structured as follows:

- Section 2 provides a general description of the technology and its operation;
- Section 3 provides a sub-system breakdown of the technology, a gap analysis and high-level TRL assessment;
- Section 4 provides a technology assessment in line with DNV RP-A203 and a subjective view on the development challenges for the system;
- Section 5 addresses the operational aspects of construction, deployment operation and maintenance of the device;
- Section 6 provides a TPL assessment of the system;
- Section 7 addresses the challenges to achieving a commercial system;
- Section 8 provides an outline technology development plan;

It is hoped that this structure will provide a progressive level of detail such that the reader can easily access the information required.

2 Device background – the Archimedes Waveswing ™

2.1 Description

The Archimedes Waveswing™ is a submerged heaving point absorber WEC designed for offshore wave energy production. The system is comprised of four main components as follows:

- An inverted canister (the "Floater") enclosing a volume of gas, that volume having a lower free-surface, said canister being submerged typically to a depth of 6m at equilibrium and free to move vertically subject to the constraints of a power take-off system. The crown of the Floater provides the wave absorbing surface;
- An inner telescopic canister (the "Silo"), concentric with the Floater and typically 50% to 75% of the diameter of the Floater comprised of two parts separated by a rolling seal with the interior being partially evacuated. The upper part of said Silo being connected to the Floater and the lower part of the Silo being restrained by e.g. a mooring system;
- The respective Floater and Silo volumes are arranged such that the buoyancy force exerted by the submerged gas within the Floater is resisted adequately by the contraction force exerted by the vacuum within the Silo, thus removing the need for additional Floater ballast;
- A structural leg which connects the Silo to an anchor via a universal joint, the internal volume within the leg being in fluid connection with the Floater gas volume so as to provide additional compressibility to the Floater gas;
- A suitable anchor designed to resist the WEC loading, particularly during survival conditions.

These components are shown in Figure 1 overleaf.

2.2 Advances from the Waveswing™ MK II

The changes to the internal arrangement of the Waveswing™ design have resulted in the following advances:

- The large gas-filled spring cylinders have been eliminated, thus removing >20 % of the device cost and improving reliability predictions;
- Removal of the 'exoskeleton' bearing structure, thus reducing weight, cost and wave loadings and reducing complexities during manufacture and deployment;
- Increase in stroke capability of the device by removing the mechanical engineering constraints inherent in the gas spring cylinders (seal velocities and ram buckling loads). This allows the use of direct-drive PTO technology which provides higher efficiency, lower cost and improved reliability.

The previous Waveswing™ MK II design is shown in Figure 2.

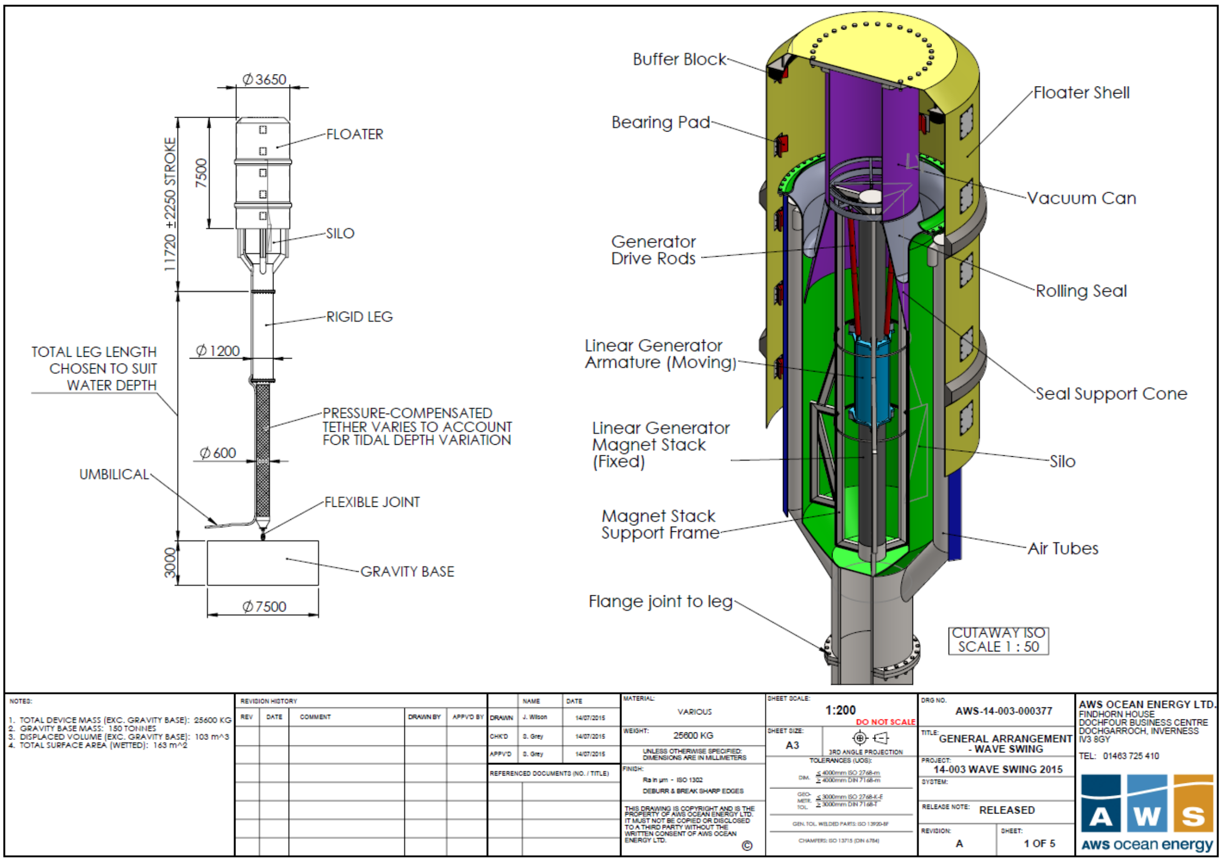

Figure 1: Basic components of the Waveswing™ MK IV

Figure 2: Previous Waveswing MK II concept

2.3 Operating principles

2.3.1 Wave power absorption mode

Operation of the WEC is conceptually simple whilst elegant. At mid-stroke the Floater buoyancy balances the vacuum chamber compression. An approaching wave crest increases the external hydrostatic pressure on the Floater causing an imbalance in forces and hence the Floater moves down-wards. This causes compression of the Floater gas which reduces buoyancy, whilst the vacuum chamber volume is decreased, raising the pressure and hence balancing the loss in Floater volume. The Floater continues to compress until the force equilibrium is re-established, thus achieving a multiplication of the wave height without the need for resonant behaviour. The wave is absorbed due to the void created through contraction of the WEC volume. The process is reversed for a wave trough. The very ‘flat’ spring curve coupled with a light Floater means that device response is not dominated by resonant behaviour and this allows tuning of the device response via the PTO for maximum power conversion.

2.3.2 Shut-down and survival

For shut-down or survival the Floater is de-pressurised and retracts to bottom-dead-centre where the lower lip of the Floater seals against a rim around the Silo. The device is held fully compressed by the vacuum force. The device pitches about the anchor joint in order to shed load in large waves. Pitch motions in excess of 20 degrees can be expected although much larger motions can be tolerated by the design.

2.3.3 Control for optimal absorption

The device has two key control ‘levers’ Firstly, the stiffness of the air spring within the Floater can be regulated by varying the volume of incompressible fluid held within the air reservoir in the leg. To increase stiffness (e.g. to limit power under high wave conditions) fluid is pumped from the lower leg chamber to the upper chamber (with a reciprocal exchange of gas via small-bore balance pipe), thus reducing the volume of gas for compression. The procedure is reversed to reduce stiffness for operation under small waves.

The second control lever is the PTO spring and damping which is actively controlled to limit stroke (thus extracting maximum energy from each stroke) and to provide inertia compensation through control of the reactive forces (i.e. feeding power into the system during part of the cycle to enhance motions and hence increase energy recovery).

The control algorithms will be developed using a detailed numerical model of the system.

2.4 Device scale and rating

The device is fully scale-able from sub-kW scale to MW scale and follows Froude scaling laws. For example a 4m diameter x 4m stroke device would be rated at 50kW whereas an 8m x 8m device would be rated at 450kW. It is intended that the first prototype system deployed in the sea will be rated at 25kW whilst it is expected that pre-commercial demonstration systems will be rated at 50kW.

2.5 Unique features of the Waveswing™ WEC

The Waveswing™ is a unique concept with significant advantages over other concepts: The hydrostatic gearing which results in wave height multiplication (heave RAOs > 1) achieves high capture factors and velocities necessary for direct-drive PTO, subsea location and de-tuned pitching structure avoids breaking waves and is inherently survivable, reaction to pressure instead of inertia enables coupling with longer waves and simple design reduces mechanical complexity, providing potential for high reliability.

2.6 Overview of intellectual property

The key principles of the Waveswing™ are protected by patent in a number of jurisdictions – see WO2008149084 (A2) for details. The priority date is 5 June 2007. A further patent application was filed in August 2015 to cover the additional hydrostatic gearing features of the MK IV design.

3 System break-down and gap analysis

3.1 System breakdown

A system breakdown has been undertaken for the Waveswing™ device in order to allow subsequent analysis of technology maturity and potential gaps. This breakdown is presented below in Figure 3 and further explanation is as follows:

- The major systems have been grouped by physical function and/or major assembly;
- Operations have been included as non-system elements which are nonetheless important from the perspective of technology development
- Numerical modelling and technology qualification activities have also been included as non-system elements as these are also important to the overall development of the technology
- System and sub-system elements have been colour-coded to represent the level of maturity. Further explanation of the colours is as follows:

Solution available (green)	A solution has been identified using existing technology and what remains is to carry out the detailed engineering design;
Solution identified (blue)	A solution has been identified however technical feasibility has not yet been finally confirmed;
Options identified (orange)	Options for potential solutions have been identified but not yet down-selected to a preferred option;
New tech required (red)	Solution not yet identified. New technology may be required to enable solution;

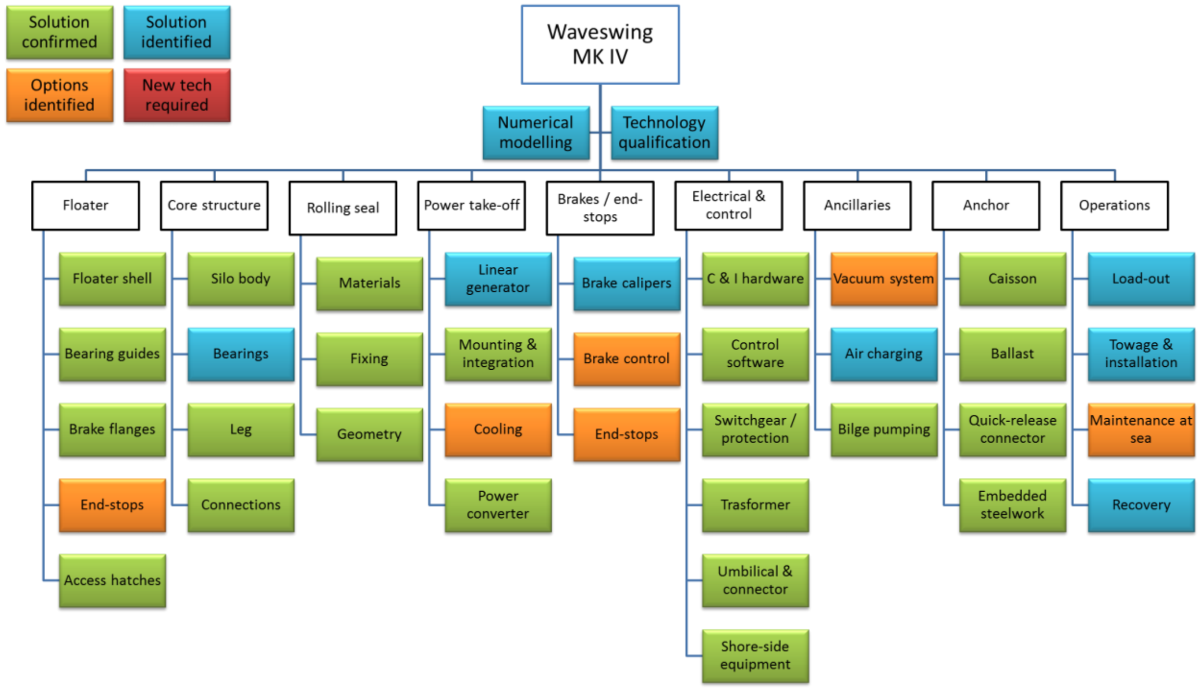

Figure 3: System breakdown and gap analysis

3.2 Gap analysis summary

The Waveswing™ has undergone significant development in the past and this is reflected in the relatively high number of 'green' systems and sub-systems. There are no areas where significant new technology is required.

Further details regarding the development status of the various sub-systems is provided in Section 4.

3.3 TRL assessment

A TRL assessment has been conducted for each of the sub-systems, together with an assessment of the likely difficulty in reaching TRL 9. This is shown below in Figure 4. Some systems have been down-rated to TRL 6 due to the fact they have not yet been demonstrated as part of the WEC system (e.g. quick-release mooring connectors which are commonly in service, hence TRL9).

The TRL scale used is set out in Appendix A.

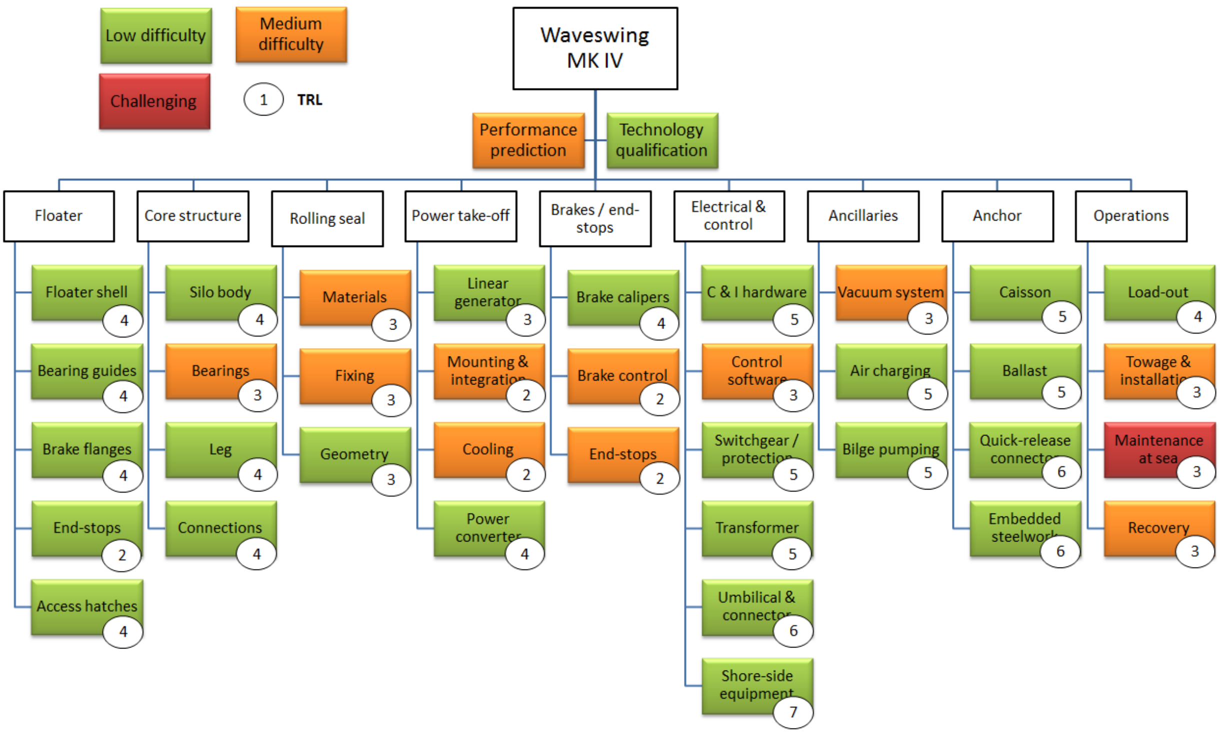

Figure 4: Waveswing™ sub-system TRL assessment

4 Sub-system development status

The DNV recommended practice for Qualification of New Technology (DNV-RP-A203) is used to categorise the various sub-systems of the device and to help develop a technology qualification plan. The following table is used as an aid in the categorisation.

Application Area	**Degree of novelty of technology**		
	Proven	Limited Field History	New or Unproven
Known	1	2	3
Limited Knowledge	2	3	4
New	3	4	4

This categorisation indicates the following:

1) No new technical uncertainties (proven technology).
2) New technical uncertainties.
3) New technical challenges.
4) Demanding new technical challenges.

Many of the technologies and/or systems proposed for use in the Waveswing™ have already been developed for use in other applications, but the use in a wave energy converter novel. More details and justification for the category assigned to each of the sub-systems is given in the following sections.

This technology assessment will be expanded in due course and used as the basis for the technology development and qualification plan moving forward.

4.1 Floater

4.1.1 Development status

The Floater comprises a truncated cylinder fabricated from rolled steel plate with appropriate stiffening. The crown of the Floater is fitted with a syntactic foam fairing for optimal hydrodynamic performance. Appurtenances include four bearing runners in stainless steel and end-stop buffer brackets. Alternative construction methods could include FRP for multiples of smaller devices.

4.1.2 Technology categorisation

Category 2 – known technology (fabricated steel in marine environment) in new application (WEC).

4.1.3 Confidence levels

Whilst the application is a new one, the engineering is not particularly challenging. Accordingly, confidence is high that a viable solution can be engineered using existing techniques.

4.1.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Detail of access for brake maintenance undefined;	Design of diver-friendly maintenance procedure in consultation with suitably experienced operators
Final hydrodynamic shape to minimise drag not defined;	CFD to optimise shape for low drag / maximum constructive wave force coupling and validate through tank test
Connection of umbilical / flying leads (depending on PTO solution);	Careful design using existing sub-sea technology solutions
Detail of lower emergency seal for storm survival;	Detailed design
Effects of marine bio-fouling, both on WEC performance and component life;	CFD to model drag with fouling present, tank testing of artificially fouled models, selection of environmentally acceptable and effective antifouling solutions

4.2 Silo

4.2.1 Development status

The Silo comprises a cylinder and associated detail fabricated from rolled steel plate with appropriate stiffening. Separate chambers are provided for the Floater air volume and the lower part of the vacuum can. A flange connection is provided to the structural leg. Key features include the outer vacuum seal attachment flange, sealing ring and bend restrictor.

4.2.2 Technology categorisation

Category **2** – known technology (fabricated steel in marine environment / sealing of rubber components to steel) in new application (WEC).

4.2.3 Confidence levels

Whilst the application is a new one, the engineering is not particularly challenging. Tyre sealing is well established technology and operates under more arduous load conditions. The flanged seal connection was proven during AWS-III single-cell tests in 2014. Accordingly, confidence is high that a viable solution can be engineered using existing techniques.

4.2.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Final dimensions to achieve desired WEC characteristics, balancing vacuum and air pressure volumes;	Output from numerical model
Final design of seal flange and bend restrictors;	Detailed design using FEA if necessary. Bench-testing on scale prototypes to confirm efficacy.
Effects of marine biofouling on drag on structure under storm conditions;	CFD to model drag with fouling present, tank testing of artificially fouled models, selection of environmentally acceptable and effective antifouling solutions

4.3 Floater Bearings

4.3.1 Development status

The bearings allow the Floater to move relative to the Silo whilst maintaining alignment between these two main elements of the WEC under varying transverse wave load. Two alternative designs are contemplated for the Floater bearings. The design developed to date uses sliding pads of low-friction bearing material (Tenmat Feroform T814) running on stainless steel strips. This design carries low technical risk but introduces friction losses and a maintenance requirement to change worn pads.

An alternative design is under consideration which will use sealed roller bearings, providing the advantage of lower losses and no maintenance requirement between major overhauls. These rollers may also integrate with alternative PTO designs.

4.3.2 Technology categorisation

Category **2** – known technology (sliding Feroform bearings in marine environment) in new application (WEC).

4.3.3 Confidence levels

Whilst the application is a new one, the sliding bearing technology is well established in other marine applications. Known alternatives exist which could improve the design. Accordingly, confidence is high that a viable solution can be engineered using existing techniques.

4.3.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Load / velocity profiles for the bearings under key conditions (steep waves);	Output from numerical model
Wear rates for bearing pads and resulting maintenance cycle;	Calculation from known data. Bench-testing of samples with degraded / fouled flanges. Use of rolling bearings as alternative to sliding pads.
Self-adjustment mechanism for pads;	Adaptation of self-adjustment used in vehicle braking systems. Develop prototypes and bench-test.
Biofouling and/or corrosion of bearing runners	Investigation of cost/benefit of using high-grade materials including non-ferrous options.

4.4 Vacuum seal

4.4.1 Development status

The vacuum seal separates the air within the Floater from the low-pressure gas within the vacuum chamber. Typical pressure differentials are in the region of up to 200 kPa. The seal is designed as a nylon reinforced EPDM rubber fabrication of conical shape. The inner seal to the vacuum can is designed as a ‘car tyre bead seal’ whilst the outer seal to the Silo can is achieved by means of a clamped flange.

Previous work has included a detailed design study by a specialist rubber fabrication company which has confirmed the feasibility of the proposed solution. Fatigue testing as part of the AWS-III diaphragm development programme is also directly relevant to this application.

4.4.2 Technology categorisation

Category **2** – known technology (reinforced rubber rolling seal – e.g. pneumatic truck suspension units) in new application (WEC).

4.5 Confidence levels

Whilst the application is a new one, the technology is established and proven in other areas. The engineering is within known limits. In particular, fatigue loading is below the endurance limit. Suppliers are confident in being able to produce a functional component which meets specification. Accordingly, confidence is high that a viable solution can be engineered using existing techniques.

4.5.1 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Final detailed design of seal geometry;	Design using FEA techniques
Final assessment of fatigue loads and S-n curve;	Use of FEA for load assessment. Long-term fatigue testing of seal samples and full seal prototypes.
Environmental attack effects;	Environmental testing of seal material samples and fatigue testing post-exposure.

4.6 Power take-off

4.6.1 Development status

The power take-off damps the motion of the Floater relative to the Silo, thereby extracting energy and converting this directly to electricity. The current design envisages a permanent magnet linear generator. The generator is located within the sealed vacuum can unit with two topologies possible – namely fixed armature or fixed magnet stack. The former alleviates potential cooling issues with the windings but leaves the magnet stack with an un-supported overhang which presents structural issues under pitch motions. Accordingly, the fixed magnet stack is preferred at present and the cooling / electrical cabling issues are recognised as requiring attention.

Alternative power take-offs are possible. An attractive option may be to combine rolling Floater bearings with belt-driven low-inertia DC generators adapted from the automotive industry (such as are being developed by Marine Design International under the WES PTO call). Belt-drive technology is however only considered feasible for lower power ratings.

4.6.2 Technology categorisation

Category **3** – technology with limited field history in new application (deployed in sealed container in WEC).

4.6.3 Confidence levels

Linear generator technology has been developed and tested extensively in laboratory conditions and the electrical engineering is well understood. However, the mechanical engineering of the machine for use in an enclosed environment, subject to rapidly changing pressure and pitch motion accelerations is entirely new. Challenges exist with the armature cooling and structural integrity of the magnet stack. There are however no challenges that require new science or technology although the engineering may require careful consideration. Accordingly, confidence is high that a viable solution can be engineered in due course using existing techniques.

4.6.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Structural integrity during operation under pitch motions;	Design review including use of FEA to asses loadings and deformations. Test of prototype system on dynamic pitching rig.
Effect of internal atmosphere on windings and magnets;	Consideration of potential effects. Bench testing within prototype vacuum can (possibly in conjunction with seal testing and pitch testing). Consideration of use of alternatives to air - e.g. dry nitrogen.
Cooling of armature windings;	Design adequate cooling paths via drive rod connections or engineer armature to be fixed whilst magnet stack moves.
Connection to vacuum top which allows radial misalignment of Floater without stressing generator bearings;	Detailed design using existing mechanical engineering solutions (e.g. universal floating joints, etc.)
Cable fatigue and connections if moving armature solution adopted	Analysis of fatigue duty and bend radius. Use of existing multi-strand cable designs and cat-track type solutions from automation industries

4.7 Brakes

4.7.1 Development status

The brake system is required in order to absorb excessive load during high waves and to prevent system damage in the event of grid loss and subsequent Floater run-away. The brakes will also lock the Floater in retracted position for storm survival following de-pressurisation. Previous designs have used variously low-pressure water pistons and high-pressure hydraulic pistons however these tend to be both expensive and loss-prone. The current design envisages a set of adapted disc brake calipers acting on a linear flange, this flange being part of the track for the bearings. Actuation of the brakes will be via an adapted vehicle traction control system with the system failing safe (i.e. clamped on) in the event of power or control system failure. Such systems are commonly applied in safety-critical applications in industry – e.g. on industrial escalators. 4 off Twinflex VKSD units would provide sufficient braking for the MK IV Waveswing™.

4.7.2 Technology categorisation

Category **3** – existing technology (industrial disc brakes) in new application (deployed in marine environment).

4.7.3 Confidence levels

Whilst the application is a new one, the science and technology aspects are not particularly challenging. Accordingly, confidence is high that a viable solution can be engineered using existing technology.

4.7.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Performance of brake on wetted flange;	Use of industry knowledge and bench test of prototypes to validate designs.
Corrosion protection and avoidance of salt build-up (warm components);	Research required - no solution as yet (fresh-water flushing not feasible)
Brake pad life under continuous operation	Use of industry knowledge and bench test of prototypes to validate designs.

4.8 Structural leg

4.8.1 Development status

The structural leg connects the Silo to the anchor via the tide-compensation member (if fitted). The leg contains two fluid compartments to allow tuning of the Floater air volume. Current design envisages each compartment as a flanged steel tube.

4.8.2 Technology categorisation

Category **1** – existing technology (fabricated steel structural member including fluid chambers) in existing application (part of sub-sea marine structure).

4.8.3 Confidence levels

Application of known technology in a known application. Accordingly, confidence is high that the final design requirements can be met.

4.8.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Fatigue loadings at flanged connections	Detailed design, FEA and fatigue analysis

4.9 Anchor connection joint

4.9.1 Development status

The anchor connection is required to provide a means of rapid connection / disconnection of the device, whilst also providing full rotation, pitch and roll. Solutions are available from two established sub-sea technology suppliers namely First Subsea (Ballgrab®) and SRP Subsea (Rocksteady). Discussions are ongoing with both companies and the final selection will be made at procurement stage.

4.9.2 Technology categorisation

Category 1 – existing technology (Ballgrap® / Rocksteady) in known application (connection of dynamic mooring components).

4.9.3 Confidence levels

As this system employs tried, tested and certified equipment, confidence is high that the solution is deliverable.

4.9.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Final load conditions;	Output from numerical model
Wear / life of the universal joint components;	Data from industry (these are standard components)

4.10 Anchor

4.10.1 Development status

The anchor is required to provide station-keeping for the WEC, adequately resisting combined buoyancy and surge forces, particularly during storm events. Significant work has been done to investigate the likely survival loads on the Waveswing™ anchor, including numerical simulation and tank testing. For the MK II Waveswing™ the design required a high density gravity-base anchor due to the magnitude of loads, including wave loading on the anchor itself in storm seas. The design used a fabricated steel frame onto which were placed bundles of steel bloom. Such anchors have been used elsewhere in the offshore industry.

The design for the MK IV has been down-rated due to the smaller device dimensions and relatively improved drag characteristics. Accordingly a circular concrete caisson is envisaged which will be ballasted post-installation with sand. The caisson will incorporate embedded steelwork for the anchor connector and suitable lifting points for installation. Similar (albeit taller) caissons are manufactured by Gaelforce for use as fish-feed barges.

4.10.2 Technology categorisation

Category **1** – existing technology (concrete gravity base anchor) in existing application (mooring of floating vessel in offshore environment).

4.10.3 Confidence levels

As this is application of established technology, there are no significant issues foreseen with engineering and delivering the anchor solution. Accordingly, confidence in delivery to TRL 9 is high.

4.10.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Final load conditions;	Output from numerical model
Final installation methodology;	Develop with experienced operators

4.11 Electrical power system

4.11.1 Development status

The functional requirements of the electrical power system are to provide: 4-quadrant control of the linear generator; power conversion and conditioning; transformation to transmission voltage; protection against fault current; and distribution of small power to ancillaries. The design has not been advanced to any significant degree at this point however similar systems were designed and built for the 690kW Waveswing™ MK 1 pilot plant. Accordingly, the systems will be developed as required using standard electrical engineering practice combined with sub-sea design experience.

4.11.2 Technology categorisation

Category **1** – existing technology (power electrical systems and power electronics) in an existing application (power control and distribution subsea).

4.11.3 Confidence levels

On the basis that this is a Category 1 system, confidence in delivery to TRL 9 is high.

4.11.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Power flows to/from the generator;	Output from numerical model
Power electronics cooling;	Application of sub-sea engineering practice
Environmental protection;	Application of sub-sea engineering practice
Access for fault intervention;	Application of sub-sea engineering practice

4.12 Control systems

4.12.1 Development status

The functional requirements of the control system are to: provide local automatic control and monitoring of all on-board systems; enable remote control of all systems in ‘direct control’ and ‘automatic’ modes; provide full fail-safe protection of the system; provide data acquisition and logging of key parameters and provide reactive control of the generator forces to optimise wave energy production. Development of the control hardware has not yet commenced although such systems are well-proven in the sub-sea industry. Software concepts for control of the generator are being developed within the system numerical modelling work.

4.12.2 Technology categorisation

Category **1** – existing technology (control system technology) in an existing application (control of sub-sea equipment). Note that the control software will be Category 2 as development work in a new application will be required.

4.12.3 Confidence levels

On the basis that this is a Category 1 system, confidence in delivery to TRL 9 is high.

4.12.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Final algorithms for control of generator damping;	Use numerical model to develop and test control strategies

5 Operations

5.1 Device construction

The Waveswing™ MK IV requires medium weight fabrication work, some limited precision machining and a degree of assembly and integration in a clean workshop environment. The assembly site should preferably be close to a quayside, however at ~ 4m diameter by 9.5m long with an all-up weight of ~ 27 ton, the device can be road-transported. The construction sequence is envisaged as follows:

- Silo constructed and painted then placed in vertical position;
- Linear generator and internal systems fitted to Silo before vacuum can including pre-fitted seal is placed over Silo and seal flange bolted up. Generator connections bolted through can top;
- Vacuum can lifted through generator stroke to test seal (requires restraint of Floater to factory floor);
- Floater constructed and painted, then lifted and fitted over Silo (requires high clearance);
- Connection made between Floater and vacuum can and temporary restraint pins fitted to Floater lower;
- Complete assembly lifted and turned to horizontal and placed on transport;
- Leg assembled to Silo at quayside before final lift onto sea-transport or launch for wet-tow to site;
- Anchor constructed on submersible barge (per Gaelforce standard practice) and floated once complete;
- Temporary top-covers fitted and sealed to anchor to prevent overtopping during wet-tow to site;

Construction of a prototype unit is expected to require around 12 to 16 weeks duration (excluding bought-in component lead times) however production units are expected to be constructed in around 4 weeks.

5.2 Deployment (e.g. Orkney location)

The deployment sequence will be similar to that developed by Global Maritime for the Waveswing™ MK II. The sequence is as follows:

- Anchor and WEC towed or transported to sheltered site (e.g. Scapa Flow) and launched using local lift capacity;
- Tow and pull-down lines attached to anchor and tails available on WEC;
- Anchor towed to site, ballasted and installed whilst pull-down lines are retained and then buoyed for recovery;
- WEC towed to site, attached to pull-down line and pulled into place using winch capacity on work-boat (e.g. Voe Viking, C-Oddesey or similar whilst umbilical tail is retained on surface;
- Final connection made to sub-sea cable via dry-mate on vessel deck;
- Electrical and control function test prior to lowering junction box to sea-bed;

The complete installation operation is planned to be completed in two 12 hour shifts.

5.3 Operation & maintenance

5.3.1 Maintenance philosophy

The design philosophy is to avoid the need for frequent maintenance through simplification of systems and reduction in component count. Function-critical systems will be duplex where economically possible to allow redundancy. Diver intervention should be designed out for production systems although a level of diver work will be permitted for prototype and early pre-commercial models. Maintenance activities will be

- Planned sub-sea maintenance tasks;
- Un-panned sub-sea intervention to rectify faults;
- Planned on-shore overhaul (target interval 5 years);
- Un-planned device recovery to rectify major faults;

A draft maintenance schedule will be prepared as an early design activity.

5.3.2 Scheduled maintenance

Planned sub-sea maintenance

- Air replenishment (from surface vessel);
- Bearing adjustment and pad replacement (if sliding bearings used);
- Cleaning of emergency pipe stabbings / control connectors;
- Cleaning of Floater crown & sides and exposed bearing tracks;

Planned on-shore overhaul (5 year interval initially)

- Replacement of Floater and generator bearings;
- Replacement of vacuum seal;
- Replacement of corrosion protection anodes;
- Weld & plate thickness inspections;
- Cleaning and re-painting as necessary;

5.3.3 Fault tolerance & sub-sea intervention

The Waveswing™ design is naturally fault tolerant as was demonstrated in 2004 during the Portugal deployment of the MK 1 device. Operation was achieved despite total loss of the control system on that device.

The device will be designed with emergency pipe connectors (stabbings) and a control connector to allow full operation from a surface vessel. This will allow recovery of the device to a safe condition, and/or investigation of faults, testing of software upgrades, etc. Connections will include Floater air, vacuum chamber gas, brake actuator power/pressure, control system power and communication, leg fluid and (if fitted) tide compensation system fluid.

To reduce the risk that the full device will need to be recovered to shore, ancillary systems will where practical be housed within external pods designed to allow disconnection / replacement by diver. These pods will be further developed for commercial systems to allow replacement by ROV. Such designs are common practice for sub-sea modules in the oil & gas industry.

6 TPL Assessment

6.1 General

Technology performance levels or TPLs are a measure developed by Jochem Weber[1] to quantify the techno-economic performance of a WEC system against a set of functional and lifecycle performance criteria. The high-level device performance metrics considered in a TPL assessment include:

- Environmental and social acceptability
- Power absorption, conversion and delivery capability
- System availability
- Capital cost
- Operational costs over the complete lifecycle

The TPL is typically inversely proportional to the LCOE of the system. The TPL assessment scale (after Weber, [R1]) is set out in Appendix B.

6.2 TPL assessment summary

An initial TPL assessment for the Waveswing™ MK IV is presented in Table 1 below.

Device metric	TPL weighting	Justification
Environmental and social acceptability	9	Low environmental impact whilst social impact is positive, particularly in remote areas. Build and deployment can be achieved safely.
Power absorption, conversion and delivery capability	8	High power absorption per unit volume of structure (best in class). High conversion efficiency through direct-drive linear generator use.
System availability	5	High survivability potential and full shut-down possible. Issues remain with access for sub-sea maintenance which could reduce availability.
Capital cost	7	Costs per unit volume are competitive with other offshore structures with potential for cost reduction through design and series production.
Lifecycle operational costs	5	Lifecycle costs dominate the LCOE equation and may be high if component reliability targets are not achieved due to inherent high intervention costs. Significant opportunity for improvement.
Projected LCOE	6	Estimated at <£330/MWh at 10MW farm scale. Expected

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[1] See: *WEC Technology Readiness and Performance Matrix – finding the best research technology development trajectory*; J. Weber (ICOE 2012)

	to reduce to below £150/MWh at 1000MW cumulative installed capacity.

All metrics – overall device TPL rating	7	Device shows potential for economic viability under supportive tariff at demonstration farm scale. Device shows potential to be competitive with other forms of renewable energy after 1000MW of installed capacity.

Table 1: TPL assessment for the Waveswing™ MK IV

6.3 Justification of TPL assessment

6.3.1 Environmental and social acceptability

The Waveswing™ MK IV is judged to have relatively low environmental impact due to its subsea location and high power density meaning that sea-bed usage is minimised. The devices are relatively small thus avoiding the need for very large construction facilities and enabling local participation in both assembly and deployment. The devices do not have any inherent health & safety issues apart from occasional use of divers for inspection and light maintenance work during the prototyping stages.

Accordingly, the environmental and social acceptability is judged to be high and contributes to a high TPL weighting.

6.3.2 Power absorption, conversion and delivery capability

The Waveswing™ system has been modelled using a sophisticated and fully-coupled time-domain model which indicates an annual average energy capture of up to 6.7 MWh/m^3 in a typical Scottish Atlantic resource. This model has not however been validated through tank testing and indeed the model requires to be revised following the recent changes to the device form in the move from the MK II design to the MK IV design. If however the model outputs are confirmed, it is considered that the Waveswing™ is highly effective as a wave power absorber in terms of energy captured per unit of structural volume.

The power conversion and delivery system is capable of high efficiency, controllability and can be engineered to provide smoothed grid-quality power. Accordingly the performance level of this element of the system is judged to be high and contributes to a high TPL weighting.

6.3.3 System availability

The Waveswing™ system has been designed with the aim of reduction in complexity and overall component count in order to increase the chances of system reliability. It is however recognised that failure of some key sub-systems will render the device inoperative and require recovery to shore for repair. This recovery operation will only be possible in relatively benign weather conditions and hence critical failures during winter and early spring could result in a significant loss of availability.

Accordingly, it will be necessary to demonstrate very high reliability at component and sub-system level for the overall system to finally become competitive with other forms of renewable energy.

6.3.4 Capital cost

The capital costs of the Waveswing™ MK IV have been assessed on the basis of a bill of materials obtained from the conceptual design. Costs and rates are based on extensive prior work on the MK II design and accordingly confidence in the cost estimates is relatively high.

The costs indicate a specific cost of ~ £1,400/annual MWh at 10MW first-farm scale. This is equivalent to ~ £3,100 per installed kW at a capacity factor of 25%. These costs compare very well with other small-scale renewable energy devices, accordingly this increases the weighting towards a higher TPL.

6.3.5 Operational costs over the complete lifecycle

The operational costs of the Waveswing™ have been assessed using a discounted cash-flow model to determine the levelised costs over the project life-cycle. This technique is described further in AWS Ocean report 15-012. The operating costs account for around 60% of the total LCOE at first farm scale and accordingly are a cause for concern. This is a problem shared by the majority of WECs.

There are significant opportunities for improvement in the LCOE through achieving high reliability and reducing the cost of intervention when this is required however currently this metric reduces the TPL weighting.

6.3.6 Projected LCOE

The LCOE for the Waveswing™ has been assessed using a sophisticated sensitivity analysis tool which makes use of Monte Carlo simulation to determine confidence limits for the LCOE as the cumulative installed capacity of devices increases. The mean LCOE estimates are resented in Table 2 below.

MW installed	**10**	**100**	**500**	**1,000**
Cost of energy £/MWh	344.5	234.0	158.8	137.4

Table 2: Mean LCOE estimates at various cumulative installed capacities

These LCOE values indicate that the technology can be competitive with other forms of renewable energy once total installed capacity reaches around 1000 MW and perhaps before. Accordingly the TPL weighting is high.

7 Challenges to achieving commercial solution

7.1 General comment

The early market for wave energy converters is likely to be in provision of power for isolated applications with requirements of a few tens of kW. Competition in such applications tends to be diesel, solar or wind power, all of which have high generation costs despite relative maturity. The potential market for such applications is significant (many thousands of devices) providing the opportunity for economies of scale in manufacturing and significant learning through multiple device operation. The investment for this learning will be spread over multiple projects rather than lumped into a single sum. Accordingly, the probability of success for achieving early commercialisation through a smaller scale route is considered to be much higher than the large-scale strategies previously followed by AWS Ocean and other WEC developers.

A small-scale route-to-market has the advantage of allowing the organic growth of SMEs (as per the Vestas example) and development of a healthy export market.

Accordingly, the challenges in achieving commercialisation are assessed in the light of a strategy to address a large market for smaller devices. For the purposes of this assessment, the technical comments relate to a Waveswing™ with rating of 50kW.

7.2 General technical & engineering challenges

Following recent innovations which allow the down-scaling of the technology, the technical difficulty and risks in achieving a commercial solution for the system have been greatly reduced. The remaining technical and engineering challenges and their possible solutions are set out in Section 4 of this report. In terms of high-level challenges likely to affect commercialisation prospects, these are summarised below and form the basis of the immediate work-plan moving forward:

Technical challenge	Identified solution / development work
Development of a full numerical model of the device to inform engineering design and economic modelling	Finalisation of existing model and tank test to validate
Development of an adequate fail-safe braking system for the Floater assembly	Use of suitably marinised industrial caliper brake systems.
Development of low-loss bearings that eliminate the risk of Floater jamming	Use of sealed marine roller bearings, possibly in conjunction with alternative PTO.
Demonstration of the adequacy of the rolling seal (including fatigue life testing);	Use of nylon-reinforced EPDM as proposed by Avon Fabrications. Lab fatigue test rig.

Integration of the novel linear generator with the rest of the WEC with particular issues around cooling of the armature windings;	Engineering detail to be addressed. Closed-circuit cooling using device external skin as heat-sink.
Engineering the ancillary systems for high reliability;	Application of established sub-sea design principles
Developing practical and affordable procedures for at-sea maintenance including surface-control and diver intervention should this be necessary.	Work with experienced local operators (e.g. in Orkney) to develop procedures and integrate enabling design features into WEC.

Table 3: Challenges to achieving a commercial system

7.3 Challenges to achieving utility scale

Modelling shows us clearly that costs increase proportional to device volume whilst performance per unit volume reduces as scale is increased due to the lower utilisation factors for larger volumes (a large volume is only used by larger waves whereas a small volume is used by all waves). Further to this there tends to be a step-change in cost for both load-out and deployment when device and anchor weights exceed that which can be handled by smaller cranes and locally-available installation vessels. Accordingly, the challenges with scaling individual devices relate more to achieving lower-cost than to the fundamental engineering. Such cost reductions are likely to arise from multiple repetitive operations. Challenges for development include:

- Development of production-line type fabrication and assembly facilities capable of handling larger devices at rates competitive with low-cost countries. This probably implies a significant level of automation;
- Development of lower-cost anchoring solutions – e.g. piled anchors which become cost effective when installed in field deployments of multiple machines;
- Development of lower-cost PTO solutions which are capable of scaling to larger powers / forces (e.g. belt-driven PMGs may provide a cheap solution at small scale but are unlikely to be feasible at higher powers using existing technology);
- Development of bespoke installation vessels and equipment;

These challenges are generic to all wave energy technologies and accordingly should not be seen as detractors from the Waveswing™ viability.

8 Technology development plan outline

Due to the significant prior work carried out in relation to the Waveswing™ system, and the reduced financial risks in working at smaller scale, the development plan is capable of being reasonably compact. A full technology roadmap has not yet been prepared however the outline of a development plan is foreseen as follows:

8.1 Phase 1 – Confirmation of performance potential

The key outcome from this phase will be confirmation that the system is capable of achieving an acceptable level of economic performance. Accordingly, uncertainties around performance given the introduction of hydrostatic gearing and the capital and operating costs of the system will be reduced. The following tasks are planned:

- Completion of analytical studies and a design review to ensure that the system modelling proceeds on a sound footing;
- Completion of the numerical model for the system, including incorporation of necessary changes to correctly represent the revised device layout and hydrostatic gearing;
- Tank testing to validate the analytical studies and numerical model, confirm hydrodynamic coefficients and demonstrate system operation to potential funders;
- Development of a parametric cost model for the device;
- Optimisation of device parameters using the performance and cost models;
- FEED of a prototype device using parameters output from numerical model to allow production of a Qualification Basis and to identify further technology risks;
- Production of a technology qualification plan to be followed in subsequent stages

These activities are anticipated to require around 12 months to complete.

8.2 Phase 2 – Sub-system development and testing

The outcome from Phase 2 will be confirmation that the critical sub-systems all operate under laboratory / workshop conditions and meet performance requirements (e.g. fatigue life), and the design has been confirmed for deployment in a first prototype. A DNV Statement of Feasibility will be sought at the end of this stage. Activities are anticipated to include:

- Build and test of a rolling seal and appropriate test rig to enable fatigue cycling under full operating loads;
- Accelerated fatigue and environmental testing of seal materials;
- Testing of linear generator within simulated vacuum can conditions with suitable inertial (pitch) loading;
- Testing of braking system and bearings under simulated conditions, possibly using quay-mounted test rig to ensure environmental exposure;
- Development of marine operations in conjunction with experienced contractors;

- Conduct further performance tests with simulated bio-fouling of Floater, Silo and leg;
- Design review and iteration following feed-back of results from component testing;
- Update of technology qualification plan and receipt of Statement of Feasibility

These activities are anticipated to require around 18 to 24 months to complete, although some activities may be carried out in parallel with Phase 1 activities.

8.3 Phase 3 – Scale prototype design and testing

The outcome from Phase 3 full demonstration of a scale prototype in real sea conditions (EMEC nursery site in Scapa Flow). The activities will include the design, build, deployment, testing and demonstration of maintenance at a scale anticipated to be 25kW.

This phase is expected to require around 24 months to complete.

8.4 Phase 4 – Pre-commercial prototype

The final pre-commercial phase will be the deployment of a pre-commercial prototype at around 50kW scale. A 'Launch Customer' will be sought for this project which will seek to demonstrate the technology in a real application.

9 Conclusion

The Waveswing™ is a simple and elegant solution to wave energy conversion. The technical issues remaining are not considered extreme and it is considered feasible to conduct a technology development and qualification programme which will resolve these issues in a relatively short period of time, with deployment of a 25kW prototype considered achievable within 3 years or less.

Appendix A: TRL scale

TRL	Basic definition	Description	Level of integration
9	System qualified through successful operations.	Technology proven in its final form and under operational conditions.	System fully integrated.
8	System development completed and qualified through test and demonstration.	Technology has been proven to production standards and under the full range of expected conditions at sea. This TRL represents the end of Demonstration. Test and evaluation of the system to demonstrate it meets the equipment specifications and requirements specifications.	Internal and external integration validated on final production design.
7	System prototype demonstrated in an operational environment.	Prototype of the operational system demonstrated in the operational environment. Full scale prototype tested in representative conditions at sea. Supporting evidence provided to show that full capability requirements can be met	All systems integrated and interfaces (internal and external) qualified in an operational environment. Full-scale system demonstration
6	System / sub-system model or prototype demonstrated in a relevant environment	Representative model or prototype system tested in a relevant environment / relatively benign sea conditions. Prototype tested in a “high fidelity” laboratory environment or in simulated operational environment.	Interfaces demonstrated at system level in a relevant environment. Sub-scale system or full-scale sub-system demonstration
5	Technology component or basic sub-system validated in relevant environment.	The basic technological components are integrated with realistic supporting elements and tested in a simulated environment. Integrated components tested in a “high fidelity” laboratory environment. Technology demonstrated in similar applications and analysis shows it is scalable to the specific application.	Interfaces demonstrated at subsystem level in a relevant environment. Impact on other systems is specified and quantified. Sub-scale demonstration
4	Technology component or sub-system validated in laboratory environment.	Basic technology components are shown to work, but at relatively “low fidelity” compared to the eventual system. Hardware demonstrated in a laboratory / small scale tank testing. Technology demonstrated in other applications (possibly at a different scale).	Interface constraints specified. The likely impact on interfaced systems is explored and can be traded.
3	Analytical or experimental critical function and characteristic proof of concept.	Technology has been shown to be viable for the application through validated analysis or experiment. Components that are not yet integrated are representative	Analytical assessment conducted to establish interface constraints.
2	Technology concept and application formulated.	Practical applications for the technology are postulated, but there is no proof or detailed analysis to support the assumptions. Patent application possible	
1	Basic principles observed and reported	Research and paper studies identify basic properties of the technology.	

Appendix B: TPL Scale (after Weber et. al. see [R1])

TPL	Category		TPL Characteristics
	Level	**Characteristics**	
9	High	Technology is economically viable and competitive as a renewable energy form	Competitive with other energy sources without special support mechanism
8			Competitive with other energy sources given sustainable support mechanism
7			Competitive with other renewable energy sources given favourable support mechanism
6	Medium	Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological or conceptual improvements may be required.	Majority of key performance characteristics & cost drivers satisfy potential economic viability under distinctive and favourable market and operational conditions
5			In order to achieve economic viability under distinctive and favourable market and operational conditions some key technology implementation improvements are required.
4			In order to achieve economic viability under distinctive and favourable market and operational conditions some key technology implementation and fundamental conceptual improvements are required.
3	Low	Technology is not economically viable	Minority of key performance characteristics & cost drivers do not satisfy potential economic viability
2			Some of key performance characteristics & cost drivers do not satisfy potential economic viability
1			Majority of key performance characteristics & cost drivers do not satisfy and present a barrier to potential economic viability