Wave Energy Scotland
Knowledge Capture Project
AWS Project 15-007

Technology Description and Status
AWS-III

Document Title:	Technology Description and Status – AWS-III
Unique Document Reference:	15-008r5
Author:	S Grey
Checked:	
Issue:	Revision 5
Date:	11 February 2016
Circulation:	WES

Copyright © Wave Energy Scotland Limited 2015

All rights reserved. No part of this work may be modified, reproduced, stored in a retrieval system of any nature, or transmitted, in any form or by any means, graphic, electronic or mechanical, including photocopying and recording, or used for any purpose other than its designated purpose without the prior written permission of Wave Energy Scotland Limited, the copyright owner. If any unauthorised acts are carried out in relation to this copyright work, a civil claim for damages may be made and/or a criminal prosecution may result.

Disclaimer

This report (including any enclosures and attachments) has been commissioned by Wave Energy Scotland Limited ("WES") and prepared for the exclusive use and benefit of WES and solely for the purpose for which it was provided. No representation, warranty or undertaking (express or implied) is made, and no responsibility is accepted as to the adequacy, accuracy or completeness of this report or any of its contents. WES does not assume any liability with respect to use of or damages resulting from the use of any information disclosed in this document. The statements and opinions contained in this report are those of the author and do not necessarily reflect those of WES.

Contents

Figures, Tables & Appendices

Revision Details

Date	Revision	Comments	Issue by
25/08/2015	0	First draft	SG
10/09/2015	1	First issue	SG
17/09/2015	2	Edited for general release	AWS
22/09/15	3	Edited to incorporate WES comment	AWS

References

Doc Ref	Title	Author(s)	Issue / date
15-001r3	AWS Wave Power Development Experience	S Grey et. al.	02/09/2015
[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-III	Multi-cell floating wave power device developed by AWS Ocean
AWS Ocean	AWS Ocean Energy Ltd
DNV	Det Norske Veritas
EMEC	European Marine Energy Centre
FEED	Front end engineering design
FOAK	First of a kind
HSCD	Half-scale cassette demonstration
IAMS	Intelligent active mooring system
kW	Kilowatt
LCOE	Levelised cost of energy
M & E	Mechanical and electrical
MTBF	Mean time between failure
MW	Megawatt
PTO	Power take-off
TLP	Tension-leg platform
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 AWS-III wave energy converter.

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 technology.

1.2 Purpose of the report

The purpose of this report is to provide a description of the current design for the AWS-III and to provide a TRL assessment of the major sub-systems, together with an assessment of AWS Ocean’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 AWS-III 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 AWS-III

2.1 Description

The AWS-III is a multi-absorber floating WEC which uses rubber diaphragms which cover air-filled cells as the primary power absorption mechanism. The devices are physically large – typically 120m by 45m for a 8 cell device rated at 2.0MW. All mechanical moving parts are isolated from the sea and contained within the device, whilst the power take-off is by means of tried-and-tested air turbine technology as developed by various companies. The device is moored using traditional catenary systems and drag-embedment anchors.

Each cell is partially submerged and with the internal air pressurised such that the face of the diaphragm sits at the mid-point of its range of motion under still-water conditions. The diaphragms are a 3-dimensional shape so that they are capable of deforming both inward and outward according to the pressure balance between the external hydrostatic pressure and the internal pneumatic pressure. The face of the diaphragm tends to remain predominantly vertical as it moves through the range of motion and thus each cell operates much like a piston wave-maker, but in reverse (i.e. absorbing waves rather than generating them). If the cell PTO damping is correctly arranged to match the hydrodynamic damping, full absorption of an incident wave is possible.

The technology can be configured on a range of hull shapes with the number of cells selected to suit conditions. The most advanced form of the AWS-III design uses a twin-hull 'proa'[1] design as shown in Figure 1. The diaphragm wave absorbers are anticipated to require regular replacement and hence are mounted on a 'cassette' which allows rapid removal and replacement at sea, whilst also facilitating full assembly, sealing and testing of the unit in factory conditions ashore.

Key components and sub-systems of the AWS-III are:

- The main structural hull;
- The absorber cassettes, including the diaphragms;
- The bi-directional air turbine-generator sets;
- The interconnecting air ducts (largely integrated into the hull) and air charging fans;
- The vessel ancillary systems (bilge pumping, etc.);
- The mooring system;
- Electrical power and control systems, including the umbilical.

All of these systems have been engineered to FEED level and significant sub-system testing has been carried out. An image of the most recent design for the AWS-III is shown in Figure 1.

---

[1] A proa is an Indonesian outrigger canoe

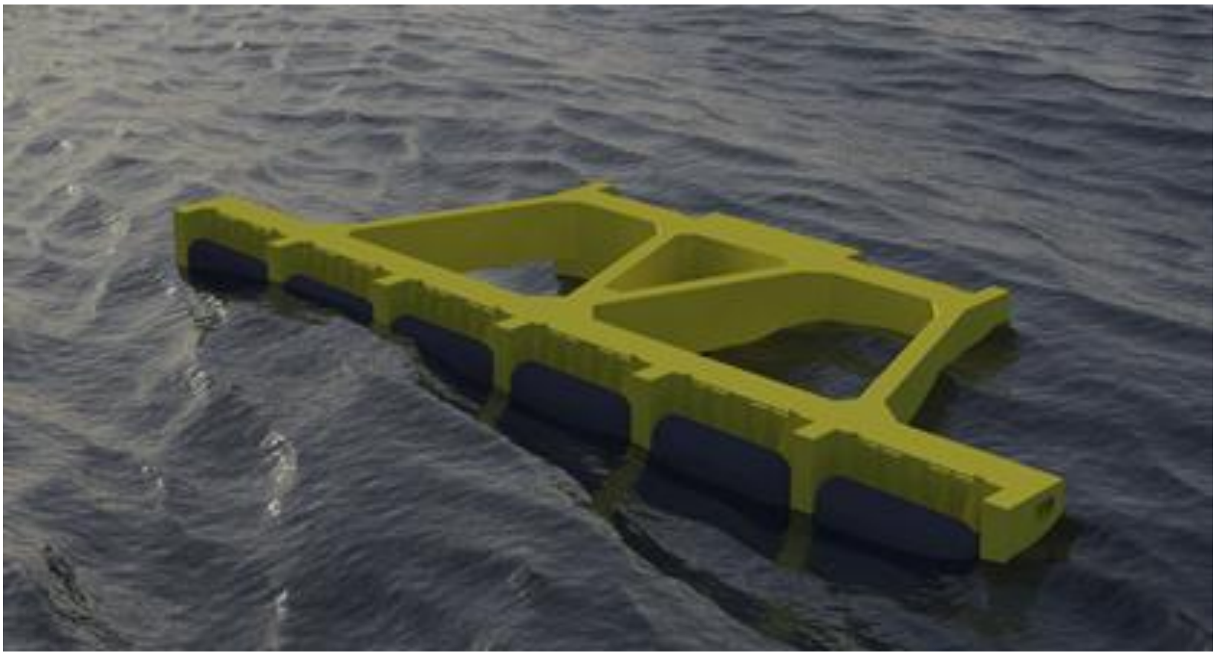

Figure 1: AWS-III Proa design

2.2 Operating principles

2.2.1 Wave power absorption mode

In operating mode the air system of the AWS-III is pressurised to balance the hydrostatic forces acting on the diaphragms. An approaching wave causes an increase in pressure, thus driving the diaphragm inwards. The process is reversed during a wave trough. The air movement caused by the change in volume of the cell drives a bi-directional turbine and associated generator to produce electricity. This concept is presented schematically in Figure 2 overleaf.

The primary power absorption mechanism of the AWS-III is the piston-like motion of the diaphragm in response to pressure from an approaching wave. The physics of the diaphragm wave absorber is almost identical to the physics of a piston wave-maker, allowing theoretical power absorption of close to 100% of incident wave power where the wave height is less than the height limit for a similarly sized wave-maker at the respective frequency. This has been confirmed by the AWS-III team by physical testing in a controlled environment.

For the current designs, each diaphragm has a rectangular area measuring 16m wide by 8m high (2m in air, 6m submerged at still water). The total swept volume of each cell is 170m^3. Mean operating pressure in the cells is ~ 35kPa (gauge), ensuring that the diaphragm sits at mid-stroke position in still-water conditions.

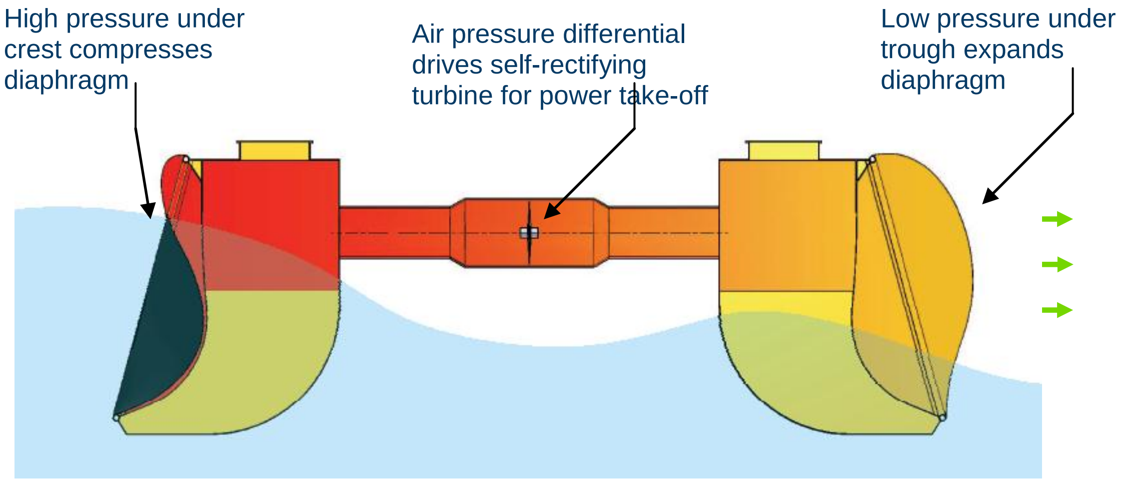

Figure 2: Schematic of AWS-III operation

Given the device geometry, it is sensitive to wave direction with optimal performance being achieved when the front of the device is in the range 20 to 40 degrees from the wave front. Observation of wave-roses for typical deployment sites shows that resource tends to have two directional peaks (e.g. NW and SW). Hence alignment of the device at a mean heading between such peaks produces best performance.

Tidal compensation is not necessary as the device is floating and the air-cushion within the cells, combined with the flexibility in the diaphragm materials eliminates any end-stop issues.

2.2.2 Shut-down and survival

Shut-down of a single cell is achieved by closing the respective isolating valves either side of the turbine. Shut-down of the whole device is achieved by venting pressure from the air system ring-main.

With the diaphragm collapsed against the cassette all wave impact loads are passed directly to the cassette structure and then on to the hull. Assuming that an inflated diaphragm is a compliant surface and that the cassette shell is rigid this may increase the shock loads acting on the cassette. A preferable survival mode in high sea states may be to increase the pressure within each cassette, fully inflating the diaphragm. The diaphragm will then cushion the impact of large waves, protecting the structure from higher shock loads. This strategy could however be prejudiced by a loss of air system integrity. Accordingly the design assumes a deflated survival mode.

2.2.3 Control for optimal absorption

To optimise the power absorption of the AWS-III there are two main parameters which can be controlled:

- Compliance of the diaphragm;
- Damping of the system

To control the compliance of the diaphragm the pressure of the ring main can be varied. This varies the shape which the diaphragm adopts and therefore varies the internal volume. Increasing the pressure will give the diaphragm a stiffer characteristic.

System damping can be controlled by changing the speed of rotation of the turbines or operation of in-line dampers designed to shed excess load.

2.3 System performance

2.3.1 Numerical modelling

The AWS-III system presents significant challenges for numerical modelling. Each of the 8 cells is a separate absorber and thus represents a separate degree of freedom. In addition, there are 6 degrees of freedom for the hull. Accordingly, this is a 14 degree-of-freedom problem. The cells are interconnected both hydrodynamically and pneumatically and these inter-connections are non-linear. In particular the hydrodynamics presents a significant challenge (the incident wave on a cassette is influenced by the absorption of the neighbouring cassettes).

AWS Ocean have commissioned several numerical modelling studies and have competed significant work in-house, however this work remains to be completed.

2.3.2 Scale model testing for power capture

AWS Ocean has recognised the challenges with generating a valid numerical model and accordingly has adopted a performance development strategy which has relied on extensive model testing.

Models have been tested at 1:10, 1:15 and 1:30 scale for performance and at 1:50 scale for global loads and survivability. Test campaigns have included single cell testing of various geometries, arrays of 3 cells, full-device tests and multiple hull-shape optimisation tests. These tests have allowed the production of a power matrices for various hull/cassette configurations. A typical test model is shown in Figure 3.

2.3.3 Conversion efficiency

The efficiency of the power take-off is to an extent dependant upon the turbine selected with several variants being suitable. For the purposes of performance modelling, AWS Ocean have assumed an overall average pneumatic-to-wire efficiency of 50% spread across all sea states. This is consistent with an advanced and well controlled Wells turbine.

Figure 3: 1:15 scale AWS-III dodecagon (12 cells) ready for launch in December 2011

2.4 Device scale and rating

The device is scale-able from kW scale to MW scale and follows Froude scaling laws. For example a nominal full-scale device comprising 8 power generating cells, each 16m wide by 8m high be rated at 2.0MW (250kW per cell) whereas a 1:4 scale device incorporated into a fish cage would have a rating of 15.6kW. The device is intended for larger-scale utility power production, however lower-cost options for remote applications where the technology can be integrated with existing structures is also under consideration.

2.5 Unique features of the AWS-III WEC

The AWS-III device has a number of unique features:

- The flexible diaphragms are highly efficient wave energy absorbers capable of up to 100% capture width in some conditions;
- The multiple-cell system provides for system redundancy and allows maintenance of part of the system whilst the remainder of the system continues to operate;
- All moving parts are contained within the sealed air system and/or hull;
- The large hull allows at-sea maintenance of all systems with the exception of the diaphragms;
- Ratings in excess of 2MW are genuine utility scale.

2.6 Overview of intellectual property

The key principles of the AWS-III have been in the public domain for several decades, however AWS Ocean has applied for patent protection in relation to key aspects of the cassette and diaphragm design.

WO2011110820 (A3) - ENERGY CONVERSION DEVICE
This patent describes a diaphragm acting as an interface between two fluids, deforming under the action of one fluid and carrying out work on the other. It includes a description of the cassette shell as a limiting device to restrict the range of motion of the diaphragm. Also makes references to limiting the outward extension through the use of tethers or straps.

WO2014068312 (A2) - DIAPHRAGM AND ASSOCIATED ENERGY CONVERSION DEVICE
This patent contains a description of a diaphragm acting as an interface between two fluids, it specifically refers to the diaphragm as a being a fabric or woven construction.

GB2509201 (A) - Wave powered pump with flexible diaphragms facing in opposite directions
This patent application describes the complete Proa AWS-III design.

GB2519282 (A) - Module for an Energy Conversion Device
This patent application relates to the improved cassette concept.

Successful performance of the system relies on third party intellectual property, such as the turbo generator, mooring system and riser. The design of some sub-systems will be contracted out to supplier organisations with the expectation that the solutions will be based on proprietary equipment.

3 System break-down and gap analysis

3.1 System breakdown

A system breakdown has been undertaken for the AWS-III device in order to allow subsequent analysis of technology maturity and potential gaps. This breakdown is presented below in Figure 4 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;

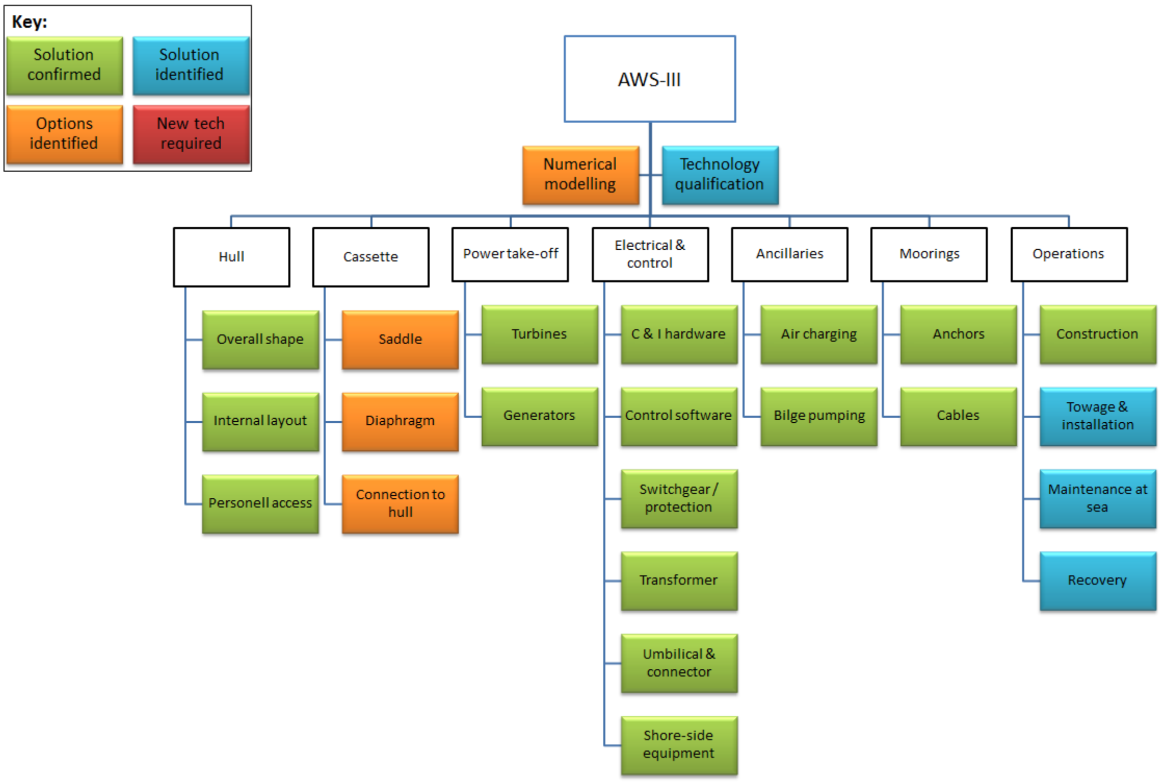

Figure 4: System breakdown and gap analysis

3.2 Gap analysis summary

The AWS-III has undergone significant development up to FEED stage this is reflected in the relatively high number of ‘green’ systems and sub-systems. However, the cassette sub-system requires further development work prior to finalisation of the design.

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. 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. on-board bilge pump systems which are commonly in service, hence otherwise TRL9). The analysis is presented in Figure 5 below.

The TRL scale used is set out in Appendix A.

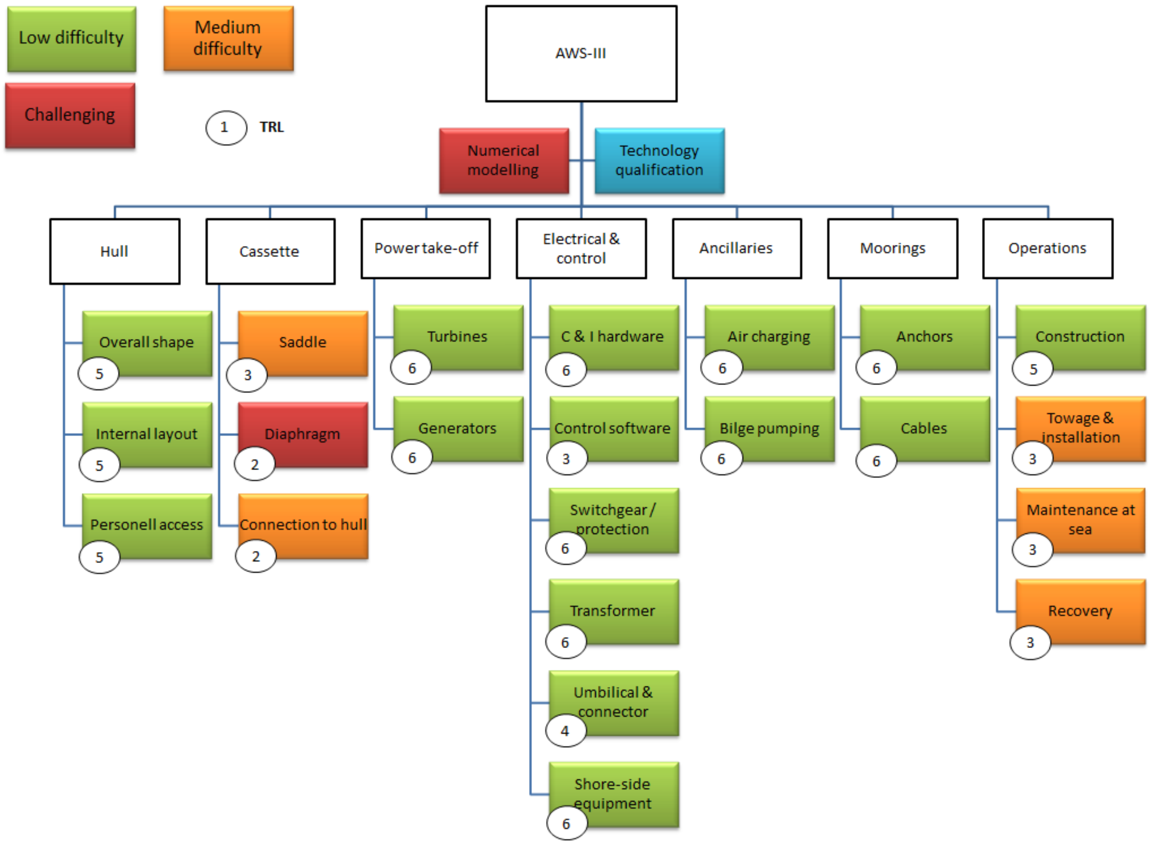

Figure 5: AWS-III sub-system TRL assessment

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 AWS-III 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 Hull

The requirements of the hull structure are that it must provide a stable, buoyant platform that has adequate strength to support the cassettes and associated systems whilst surviving the full range of environmental conditions, including a 100 year storm, and have an operating life of at least 20 years with planned maintenance.

4.1.1 Development status

There are a number of possible hull variants including a dodecagon shape, a catamaran, a 'delta' and an unequal catamaran of 'proa' (as shown in Figure 1).

A full FEED study has been carried out in conjunction with a leading European shipyard. This study included generation of scantlings and a full set of arrangement drawings for the hulls. Structural loadings have been confirmed through 1:50 scale tank testing.

Accordingly, the development status of the proa hull design is considered to be well advanced, however there remains an un-resolved issue relating to the dynamic stability of the hull. This instability is caused by the transfer of buoyancy from one cell to another and is subject to a positive-feedback effect. Essentially any error in trim of the hull will increase the pressure on the cells which are more submerged and will relieve pressure on the more exposed cells. This results in compression of the submerged cells, thus further reducing buoyancy whilst the exposed cells inflate and increase in buoyancy. The known solutions are either (a) to increase the water-plane area of the hull or (b) to tension-tether the hull as per a tension-leg platform (TLP).

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 engineering solution can be engineered using existing techniques.

4.1.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Eliminating the free-surface instability issue	Novel hull forms, additional hull water-plane area or tension tethering (possible only in deep-water locations)

4.2 Cassette

The cassette assembly is designed to allow pre-assembly, sealing and factory testing of a diaphragm prior to installation onto the AWS-III device. The cassette consists of three main sub-systems:

Saddle

The saddle comprises a rigid concave shell which provides a mechanical attachment point for the diaphragm. It is shaped to provide support to the diaphragm when unpressurised or forced back into the saddle and to transfer loads through to the hull.

Diaphragm

The diaphragm is a flexible sheet which provides an air tight interface between water on the seaward face and process air on the internal side. The material must be compliant but also be very strong to handle large tension loads.

Connection to hull

The hull connection must both allow rapid and secure installation of the cassette offshore whilst also transferring loads from the cassette into the hull. These loads include both the buoyancy forces generated by the cassette and the surge forces on the exposed vertical area caused by incident waves. As the cassette has a significant surface area the loads are significant and accordingly the design of a dis-connectable system is challenging.

4.2.1 Development status

Saddle

Significant work has been carried out in the development of the saddle with key considerations being the shape required to relieve the diaphragm loading under severe wave conditions and the shape required for efficient wave absorption. A complex 3D shape has been developed, however as we learn more about cell performance this shape is likely to change.

The current design includes features such as a sump, drainage channels, instrumentation ports, bumper bars and air duct connection. The complex shape was fabricated successfully as part of the half-scale cassette demonstration programme.

The design however remains expensive and hence further work is required to find alternative and more cost-effective cassette solutions. Several innovative and promising concepts have been identified.

The back of the saddle for the half-scale cassette is shown overleaf in Figure 6.

Figure 6: Half-scale cassette (back view) during load-out in 2014

Figure 7: Half-scale cassette under test - diaphragm fully inflated

Diaphragm

Diaphragm development is ongoing and a partial solution was tested during the half-scale cassette demonstration (HSCD) project in 2014 (Figure 7). Unfortunately the performance of the materials in fatigue was not acceptable and accordingly further development is required.

Significant work has been carried out in terms of development of the diaphragm shapes for efficient power absorption and effective load carrying in conjunction with the saddle. Work has also been carried out on diaphragm fabrication techniques and jointing. Work remaining is to further develop the diaphragm material to provide the right combination of flexibility, stretch and fatigue strength.

Recent work on performance suggests that benefits may be realised by adjusting the diaphragm shape however this will result in the need to re-evaluate loads and fatigue duty. Accordingly, whilst AWS Ocean has accumulated significant knowledge of the issues which drive the development of the diaphragm, we are not yet content that we have arrived at the optimum solution.

Connection to Hull

A number of options have been investigated in relation to the cassette connection to the hull using experienced offshore engineering consultants. The final design has not yet been selected.

The solution successfully developed and deployed for the HSCD project comprising a bolted cantilever connection extending from the top of the saddle to pre-installed steel beams anchored to the caisson. This removed the need for subsea installation work and diver support however this solution is not thought to be viable for a full-scale cassetted deployed in an exposed location.

4.2.2 Technology categorisation

Category **4** – unproven technology (composite diaphragm in marine environment) in new application (WEC).

4.2.3 Confidence levels

Developing the cassette sub-system to provide the required through-life performance is a significant challenge, however AWS Ocean has made excellent progress to date and remain confident that a final solution can be engineered.

4.2.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Uncertainty - fatigue life/durability of diaphragm material	Further material testing required which is representative of in-service conditions Validated FEA model of diaphragm required
Uncertainty - Diaphragm shape	Modelling to determine optimum shape of diaphragm Validated FEA model of diaphragm required
Uncertainty – edge connection	Determine connection method of diaphragm to saddle which is simple, quick & reliable
Saddle shape	Using diaphragm shape & modelling, determine shape of saddle
Uncertainty - Loading on Hull connection	Using saddle shape and FEA, determine loading on saddle
Uncertainty - Design of hull connection	Use FEA to design hull connection which can survive the identified loads

4.3 Power take-off

The functional requirement for the PTO is to convert the reciprocating airflow resulting from the diaphragm movement into electrical power whilst also providing the ability to vary the damping to suit the incoming wave conditions and hence maximise power extraction.

4.3.1 Development status

Air turbine development for oscillating water column type WECs has been ongoing for two decades and the Wells turbine is proven technology developed to TRL 8.

Alternative impulse-type turbines have also been developed and are claimed to provide higher efficiencies. These systems remain un-proven.

4.3.2 Technology categorisation

Category **2** – known technology (Wells turbine-generator sets) in new application (closed-circuit air system inside WEC).

4.3.3 Confidence levels

Whilst the application is a new one, the engineering is not particularly challenging. Accordingly, confidence is high that the solution is viable.

4.3.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Matching turbine damping capability with cell dimensions	Further hydrodynamic and numerical system modelling
Development of systems for power shedding in large waves	Development of existing damper systems
Development of equipment layouts to enable on-board maintenance	Routine engineering

4.4 Electrical & control

The functional requirements for the electrical and control systems are as follows:

- Provide power interconnection of turbine-generator sets running at different continuously variable speeds at low voltage;
- Provide power conditioning, voltage / frequency regulation and voltage step-up to HV for transmission ashore;
- Provide LV and HV switching and protection;
- Provide instrumentation and sensing of turbine-generator sets, cell conditions, ring-main conditions and other device parameters;
- Provide control of the individual turbine-generator sets for start-up, variable-speed operation in response to damping requirements and safe shut-down;
- Provide control of vessel auxiliaries (ventilation, pumping, lighting, emergency power, etc.);
- Provide remote control and communications capability;

Whilst the requirements are significant, none represent a new engineering challenge and all can be met using existing technology.

4.4.1 Development status

No detailed design work has been carried out for the electrical and controls system.

4.4.2 Technology categorisation

Category **2** – known technology (power and controls in an offshore vessel) in new application (WEC).

4.4.3 Confidence levels

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

4.4.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Development of control algorithms for matching turbine damping to incoming wave resource for maximum energy extraction	Numerical modelling and validation through scale test.

4.5 Ancillaries

The functional requirements to be met by the ancillary systems are as follows:

- Air charging of the pneumatic turbine ring-main to operating pressure of ~ 320 mBar and maintenance of pressure whilst allowing for system leakage;
- To provide for vessel operation, including bilge pumping, machinery space ventilation, internal lighting, fire suppression and crew welfare facilities;

Systems will be similar to those deployed on other offshore vessels.

4.5.1 Development status

An air charging system was tested and proven on the half-scale cassette demonstration project. The remainder of the systems have not been addressed in detail however outline scope was considered during the FEED for the Proa FOAK.

The systems are considered to be typical of offshore vessels and accordingly can be developed as and when required using standard engineering practice.

4.5.2 Technology categorisation

Category **2** – known technology (offshore vessel ancillary systems) in new application (WEC).

4.5.3 Confidence levels

Whilst the application is a new one, there are no engineering difficulties forseen. Accordingly, confidence is high that the required systems can be engineered using existing techniques.

4.5.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
None foreseen	

4.6 Moorings

The moorings are required to hold the AWS-III on station in all conditions whilst providing the required response to enhance power absorption by the WEC.

The mooring system will comprise 3 key sub-systems or components:

- Anchors – currently scoped as drag-embedment anchors (e.g. Vryhof Stevpris);
- Cables – various configurations available including chain catenary, synthetic line and in the future possibly IAMS;
- On-board systems – including fairleads, tensioning equipment and means of securing the lines;

The technology for all of these systems is available in mature form, although to reduce the costs and mooring footprint for the AWS-III, the use of novel cables (e.g. parallel strand nylon or IAMS) will be required. In deeper water with low tidal range a tension-tether system could be feasible and this may provide a solution to the dynamic instability issues highlighted in Section 4.1.4. Again the technology for tension mooring of large structures is well established.

4.6.1 Development status

Various studies have been carried out in order to determine the mooring conditions for the AWS-III including 1:50 scale survival tests for both a proa and a dodecagon shaped hull. Accordingly the design requirements are understood at a reasonable level by AWS Ocean.

Designs have been prepared for the various possible mooring configurations and these have confirmed a range of feasible options. Studies have not however yet investigated the linkages between the mooring design and the dynamic stability of the hull, nor the effect on power capture of various configurations.

4.6.2 Technology categorisation

Category **2** – known technology (moorings for offshore structures) in new application (WEC).

4.6.3 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.

4.6.4 Development challenges and mitigations

Challenge / uncertainty / risk	Mitigation / development activities
Cost of traditional mooring configurations	Qualification of parallel strand nylon for use in permanent moorings (project ongoing)
Effect of mooring configuration on hull stability and power capture performance	Numerical modelling and subsequent validation through tank testing
Opportunity for cost reduction through shared anchor points in multi-device farms	Future work dependant on preferred configuration for single units

5 Operations

5.1 Device construction

The AWS-III is a physically large device measuring 120m long by 45m wide and 10.5m high (Figure 8). The overall structure weight is in excess of 2,500 tonne before fit-out and around 4,400 tonne once fully equipped and ballasted.

Accordingly, the construction of the AWS-III requires a medium capacity shipyard capable of series production and fit-out of large hulls.

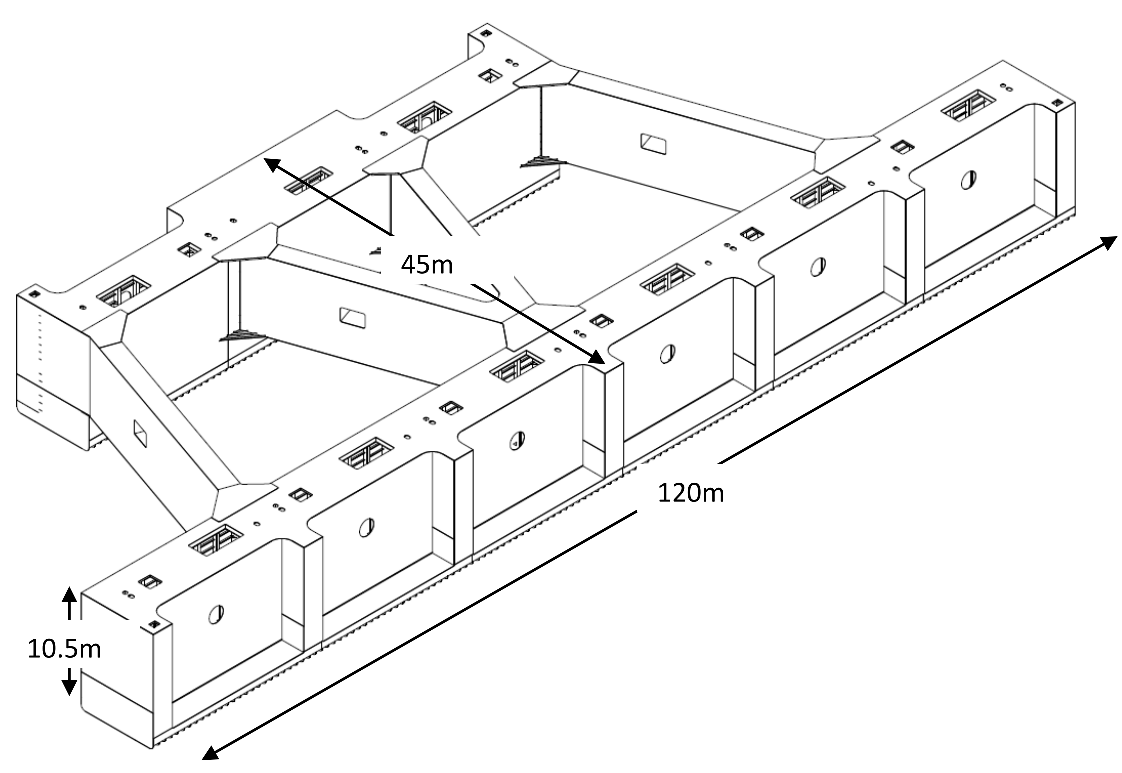

Figure 8: AWS-III isometric extracted from detailed design drawings

Initial investigations have shown that at present there is no suitable shipyard in the UK which is capable of producing the AWS-III units in volume and at a reasonable cost. Discussions with European ship-builders have produced a viable solution for construction where bare hulls are built in Eastern Europe and transported to a final assembly / fit-out yard in (e.g.) the Netherlands.

5.2 Deployment (e.g. Orkney location)

The deployment sequence has not yet been considered in detail however it is expected to be as follows:

- Moorings installed on site using suitable vessels (depends on final design);
- AWS-III units towed to sheltered waters (e.g. Scapa flow);
- Cassettes fitted to AWS-III units and final pressure testing completed;
- AWS-III units towed to deployment site and connected to moorings;
- 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 expected to take several weeks.

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. The AWS-III WEC is designed to allow continued operation of cells even when once or more cells have been isolated for maintenance. The very large and stable hull with significant machinery spaces allows for on-board maintenance of all ancillary systems and the possibility for procedures such as turbine bearing shell changes to be carried out in-situ.

Overall, the maintenance tasks will fall into the following categories:

- Planned at-sea maintenance tasks;
- Un-planned at-sea intervention to rectify faults;
- Planned on-shore overhaul of cassettes (target interval 5 years);

It is intended that the device hull should remain on station for considerable periods, only requiring return to sheltered water for detailed inspection and careening at around 10 year intervals.

5.3.2 Scheduled maintenance

<u>Planned at-sea maintenance</u>

- Maintenance of all on-board ancillary systems;
- Replacement of turbine bearing shells (10,000 hour life minimum);
- Maintenance of electrical systems and testing of protection circuits;
- Replacement of cassettes to allow on-shore refurbishment;
- Moorings inspection and line replacement;

Planned on-shore overhaul (5 year interval initially)

- Refurbishment of cassettes;
- Turbine overhaul;

Planned maintenance in sheltered waters

- Plate thickness inspections;
- Hull cleaning;
- Replacement of corrosion protection anodes;
- Painting of topsides;
- Maintenance of ancillary systems;

5.3.3 Fault tolerance

As noted previously, the AWS-III is naturally fault tolerant due to the multiple cell design. Protection circuits will be designed to isolate a leaking cell on an automatic, fail-safe basis.

6 TPL Assessment

6.1 General

Technology performance levels or TPLs are a measure developed by Jochem Weber[2] to quantify the techno-economic performance of a WEC system against a set of functional and lifecycle performance criteria [R1]. 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 AWS-III device is presented below:

Device metric	TPL weighting	Justification
Environmental and social acceptability	8	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	5	Power absorption per unit volume of structure is acceptable (around 4.7MWh/m^3 in Scottish Atlantic resource) but could be improved if cell interactions are improved.
System availability	5	High survivability potential and full shut-down possible. Key issue remaining is diaphragm durability which will be resolved through further work.
Capital cost	5	Costs per unit participating volume of absorber are relatively high at £15K/m^3.
Lifecycle operational costs	5	Lifecycle costs represent less than 20% of the LCOE and accordingly are considered acceptable, subject to diaphragm life.
Projected LCOE	5	Targets can be met through technology advances already identified.
All metrics – overall device	5	In order to achieve economic viability under favourable

---

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

TPL rating	conditions some key technology improvements are required. These have been identified.

Table 1: TPL summary for AWS-III

7 Challenges to achieving commercial solution

7.1 General comment

AWS Ocean have been working to commercialise the AWS-III for several years with the backing of major OEMs and the support of potential utility customers. In common with other WEC developers we have met with a number of challenges to commercialisation of a technology at this scale. The key challenge is the cost and risk inherent in large-scale prototypes and early demonstration projects. For example, the AWS-III FOAK budget exceeds £25 million and the cost of a pre-commercial farm is in excess of £100 million. Clearly an investment of this value in unproven technology is not something which investors will contemplate.

A solution would appear to be to test the technology at partial scale, however the key technical issues with the AWS-III are the loading and durability of the diaphragm and due to Froude scaling issues, partial scale tests do not provide a representative qualification test for the full-scale device.

AWS Ocean has tried to resolve this problem by proposing tests of a limited number of full-scale cassettes and if the fundamental TPL can be improved, then this may prove to be a viable route forward for qualification of the diaphragms and cassettes. This will not however provide qualification of the device performance and a fully representative FOAK at full scale will be required eventually as part of the qualification programme.

7.2 General technical & engineering challenges

The remaining technical and engineering challenges and their possible solutions are set out in Section 4 of this report and as noted in Section 6.2 the device TPL is only medium indicating that the identified solutions to some significant technical challenges must be developed before the device can be considered as a commercial prospect for utility scale power. The high-level challenges to be addressed are summarised in Table 2 overleaf.

7.3 Challenges to achieving utility scale

Setting aside the device-specific technical challenges, the commercialisation challenges are considered to include:

- Development of production-line type fabrication and assembly facilities capable of handling very large devices at rates competitive with low-cost countries. This probably implies a good level of automation, but also requires significant real-estate with deep-water access and large-scale investment to develop the facilities;
- Development of on-shore cassette service bases close to the deployment site;

- Development of bespoke installation vessels and equipment;

These challenges will be addressed once the TPL for the device has been advanced to a higher level.

Technical challenge	Identified solution / development work
Development of a full numerical model of the device to enable device optimisation	Significant challenge - possible PhD project?
Further development of the diaphragm solution so as to provide required durability and fatigue life whilst maintaining absorber performance;	Testing and implementation of identified solutions.
Free-surface buoyancy effects	Development of a tension mooring solution.
Development of the cassette to reduce material content and hence cost, whilst allowing a feasible offshore exchange mechanism.	Various novel solutions have been identified by the AWS Ocean team and show considerable promise.
Optimising the PTO to maximise power absorption and conversion	Further numerical modelling of both the absorber and the PTO is required to confirm optimum.
Engineering the ancillary systems for high reliability;	Application of established sub-sea design principles

Table 2: Summary of technical challenges to achieving a commercial solution

8 Technology development plan outline

An outline technology development plan is set out in Table 3. This plan reflects the challenges presented in Table 2 however it will also be necessary to structure the programme in a way which can provide investors with confidence in the technology without major expenditure.

Activity	Outcome	Timescale
Development of parametric cost model and subsequent optimisation	Demonstration that an acceptable TPL can be achieved and identification of the technology steps which must be taken to enable a viable product	3 months
Concept studies to produce solutions to required technology steps	Confirmation that the required technology steps are technically feasible and determination of the cost and timescale for development to TRL 5.	3 – 6 months
Business case evaluation (Concept Gate Review)	Confirmation that the overall business plan for the technology is deliverable and will provide acceptable returns to investors	Start + 6 months
Concept development, sub-system prototyping and qualification, overall device FEED	Partially qualified sub-systems to TRL 5 and overall device design which delivers functional and performance as required by the business case	2 years
Specification Gate Review	Confirmation that the technology development programme has met objectives, that the device specification is clear and that the business case for the technology remains on track. Release of funds for detailed design.	Start + 2 – 3 years
Detailed design of FOAK	Detailed designs ready for manufacture	6 months
Design Gate Review	Confirmation that the detailed designs meet the specification, that construction costs are acceptable and business case remains on track	Start + 3 – 4 years
Construction of FOAK	Validation of device performance at full scale.	18 months

Table 3: Development plan outline

9 Conclusion

The AWS-III is a utility-scale solution to wave energy conversion which initially showed commercial promise (see AWS Ocean report 15-012) however detailed design work has revealed issues which have resulted in significant cost increases.

The AWS Ocean team remains confident that the cost issues can be resolved through optimisation and that a fresh approach to the diaphragm challenge will yield solutions. Several promising ideas were put forward during 2013 however these have not been investigated due to lack of resource.

The next key activity is to carry out the parametric cost modelling. This could be done in conjunction with developing wider techniques for use in assessing other WEC projects. If this work indicates that a route to commercial success is possible then the technology development plan can be developed and implemented once funding is available.

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