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Technology Description and Status
Electric Eel

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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
AMI	Artificial Muscle Inc.
AWS	Archimedes Waveswing
AWS Ocean	AWS Ocean Energy Ltd
CEL	Coupled Euler Legrangian
DNV	Det Norske Veritas
EAP	Electro-active polymer
EMEC	European Marine Energy Centre
EPAM	Electro-active polymer artificial muscle
FEED	Front end engineering design
FRP	Fibre-reinforced plastic
HMRC Cork	Hydraulics and Maritime Research Centre, Cork
IAMS	Intelligent active mooring system
kW	Kilowatt
LCOE	Levelised cost of energy
M & E	Mechanical and electrical
MTBF	Mean time between failure
MW	Megawatt
Pilot plant	The 690kW AWS plant deployed off Portugal in 2004
PTO	Power take-off
SRI	Stanford Research Institute (California)
TPL	Technology performance level
TRL	Technology readiness level
WEC	Wave energy converter
WES	Wave Energy Scotland Ltd
UV	Ultra-violet

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 Electric Eel 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 technology.

1.2 Purpose of the report

The purpose of this report is to provide a description of the current design for the Electric Eel 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 Electric Eel 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 Electric Eel

2.1 Description

The Electric Eel is a submerged pressure differential wave energy converter designed for offshore wave energy production. A bulge wave is generated in the tube by the action of the ocean waves which increases in size as it travels down the tube. The bulge wave creates circumferential strain of the thin tube walls, effectively absorbing wave power which can be converted to electrical energy by the PTO. Batteries or capacitor storage can be used to smooth the output. The system is comprised of four main components (Figure 1):

- A rigid nose cone which provides support and attachment of the distensible tube to the mooring solution;
- A distensible tube of a suitable stiffness and strength – the stiffness will be broadly tuned to the expected sea conditions to allow optimum power capture. The tube is filled with a fluid which can be pressurised to provide an initial tension in the tube material;
- A PTO which can act as an actuator or generator and is integrated into the distensible tube. Deformation of the tube can be controlled to allow optimisation of device performance in varying sea states. An electro-active polymer active muscle (EPAM) or hose pump (hydraulic) PTO would be well suited to this application;
- A mooring solution comprising anchor(s) and line(s) which allow the Electric Eel to weathervane to the prevailing wave direction;

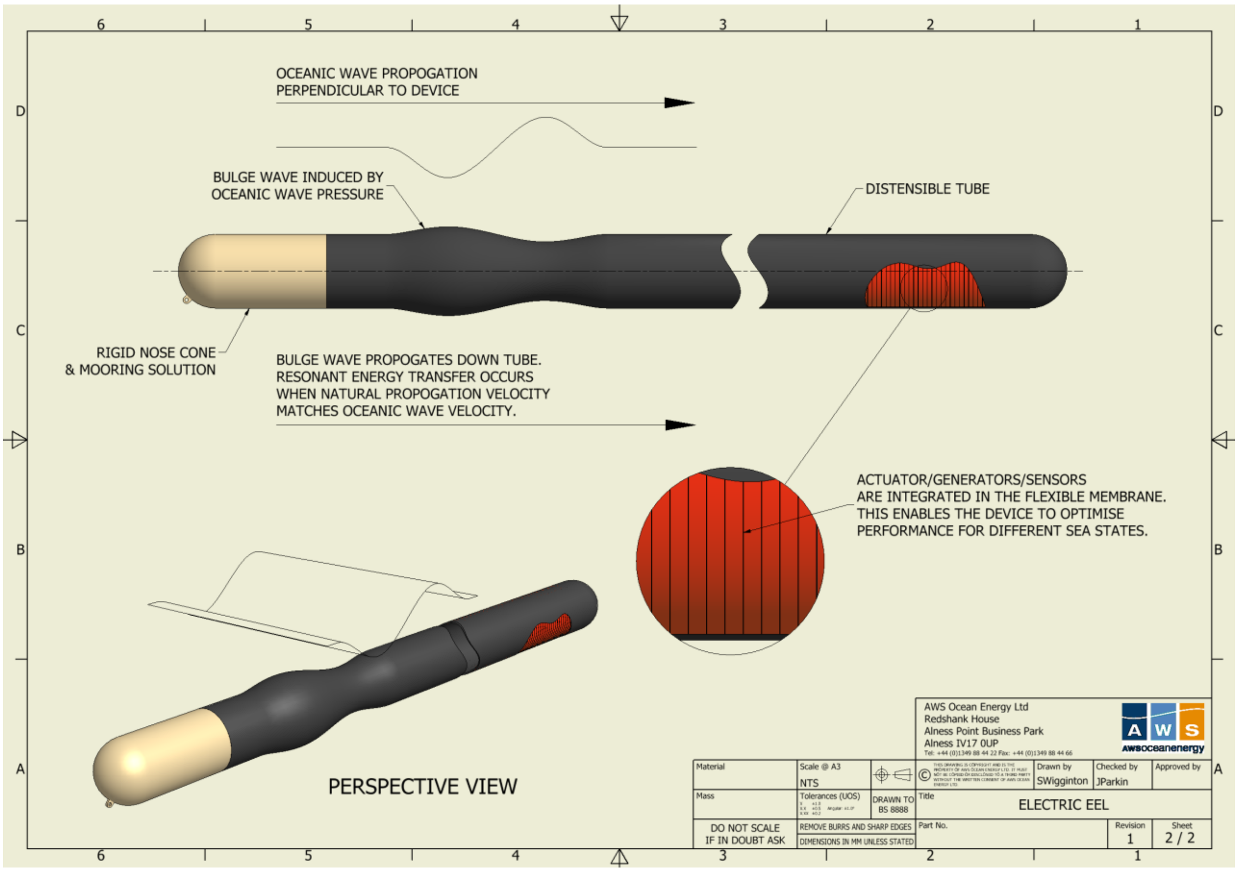

Figure 1: Basic components of the Electric Eel

2.2 Advances from the Anaconda WEC

Although the Electric Eel has the bulge wave phenomenon in common with the Anaconda WEC, the Electric Eel makes a number of changes to the way the device is controlled and how the power is captured.

- Constant power extraction

  Through the use of multiple PTOs embedded along the length of the device, power can be extracted as the bulge wave moves along the device rather than waiting for the bulge wave to reach a single PTO at the end of the tube. This avoids the bulge wave reaching saturation – a point where it can no longer absorb energy due to strain limitations, hence enabling longer tubes.

- Tune-ability

  The tuning of the device is related to the stiffness and dimensions of the tube. As the PTO is embedded within the tube material it can be controlled to provide a variable stiffness, optimising the tuning of the device to the sea-state.

- Higher efficiency PTO

  Electroactive polymers have demonstrated high efficiencies of up to 80-90% under the right conditions.

- Fewer mechanical moving parts

  Electroactive polymers do not require any moving parts, avoiding the use of bearings and lubricants with their accompanying maintenance schedules

2.3 Operating principles

2.3.1 Wave power absorption mode

A bulge wave is generated in the tube by the action of the ocean waves which then travels down the tube, growing and absorbing energy until in equilibrium with system losses. Once equilibrium is reached no further power will be absorbed along the length of the device. With a solitary PTO at one end of the device this would result in wasted length of the tube. A distributed PTO is proposed which converts energy along the length of the device, removing the wasted length. The PTO (consisting of either an electro-active polymer artificial muscle (EPAM) or hydraulic system converts the deformation of the tube into useful electrical energy.

2.3.2 Shut-down and survival

Flexible, lightweight structures can be well suited to good survivability. The Electric Eel WEC had not been developed far enough to determine the optimum shut-down and survivability conditions.

2.3.3 Control for optimal absorption

Control of the Electric Eel WEC has not yet been developed however it is expected that there will be two primary control functions:

Firstly, the tuning of the bulge wave is dependent on the geometry and material properties of the tube. As the PTO is embedded into the tube walls it can be controlled resulting in a controllable stiffness of the device. This allows the Electric Eel to be tuned to suit the wave conditions.

Secondly, the PTO can be used to actively create the bulge wave which is then further propagated by wave action (without this the bulge would take some distance to grow to a size where energy can be extracted).

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 level. A candidate device of 7m diameter and 155m length was sized at 750 kW. Larger devices have been sized up to a rating of 5.25 MW.

2.5 Unique features of the Electric Eel WEC

The Electric Eel is a unique concept with significant advantages over other concepts:

- The distributed PTO allows for smoother power generation than the Anaconda;
- The same distributed PTO allows for control of the device stiffness, tuning it to the conditions which it encounters;
- Electro-active polymers offer the potential for higher conversion efficiencies than conventional PTOs;
- EAPs have no mechanical moving parts avoiding bearings & lubricants in the PTO and reducing maintenance requirements.

2.6 Overview of intellectual property

The key principles of the Electric Eel are protected by patent in a number of jurisdictions – see WO2009106836 (A3) for details. The priority date is 28 February 2008.

Electro-active Polymer (EAP) IP is owned by SRI of the USA. This was sub licensed to Artificial Muscle Inc. (AMI) who develop EAP devices and generators for bespoke and series production applications. AMI has sub licensed EAP generation for wave energy applications to Hyperdrive Corporation of Japan, who were developing the technology for powering navigation buoys.

Since the work in 2007, AMI have been acquired by the Parker Hannifin Corporation.

3 System break-down and gap analysis

3.1 System breakdown

A system breakdown has been undertaken for the Electric Eel device in order to allow subsequent analysis of technology maturity and potential gaps. This breakdown is presented below in Figure 2 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;

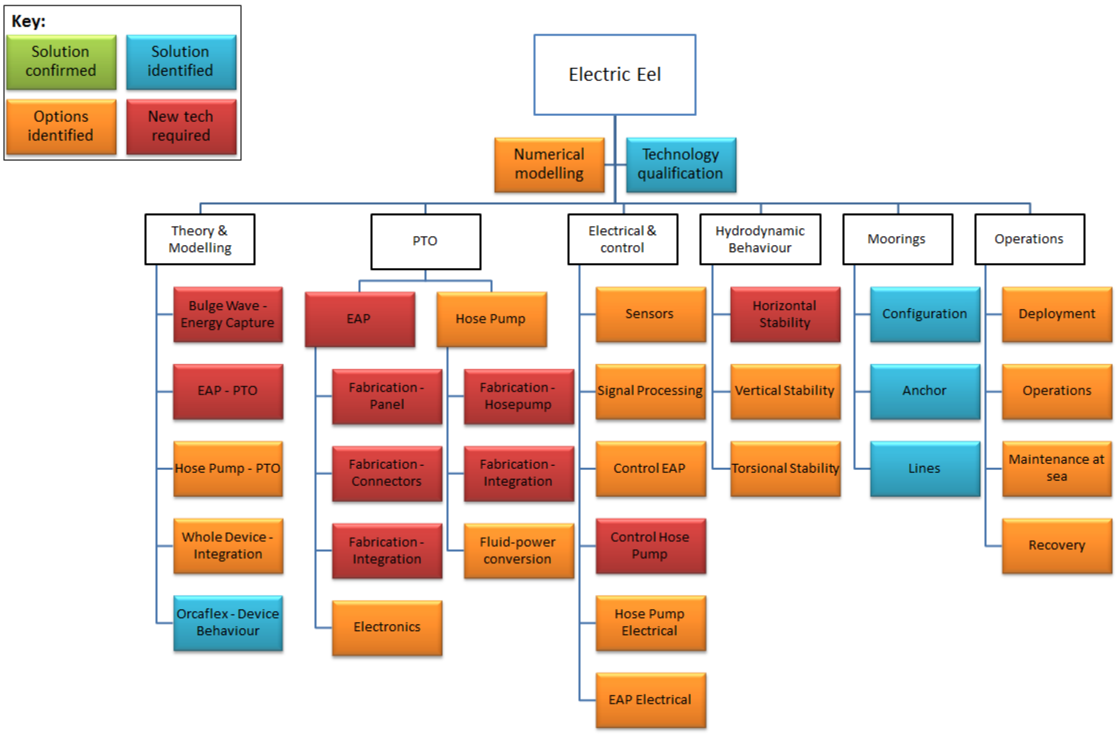

Figure 2: System breakdown and gap analysis

3.2 Gap analysis summary

The Electric Eel includes advancements to technologies which have only been tested at a small scale under very controlled loading. Whilst it promises great advancements in wave energy conversion, there are a number of areas where significant new technology is required. Some areas such as moorings and modelling software have solutions which have been identified however limited development means there are no areas with confirmed solutions.

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. anchors connectors which are commonly in service but not tested in this application, hence TRL6).

The TRL scale used is set out in Appendix A.

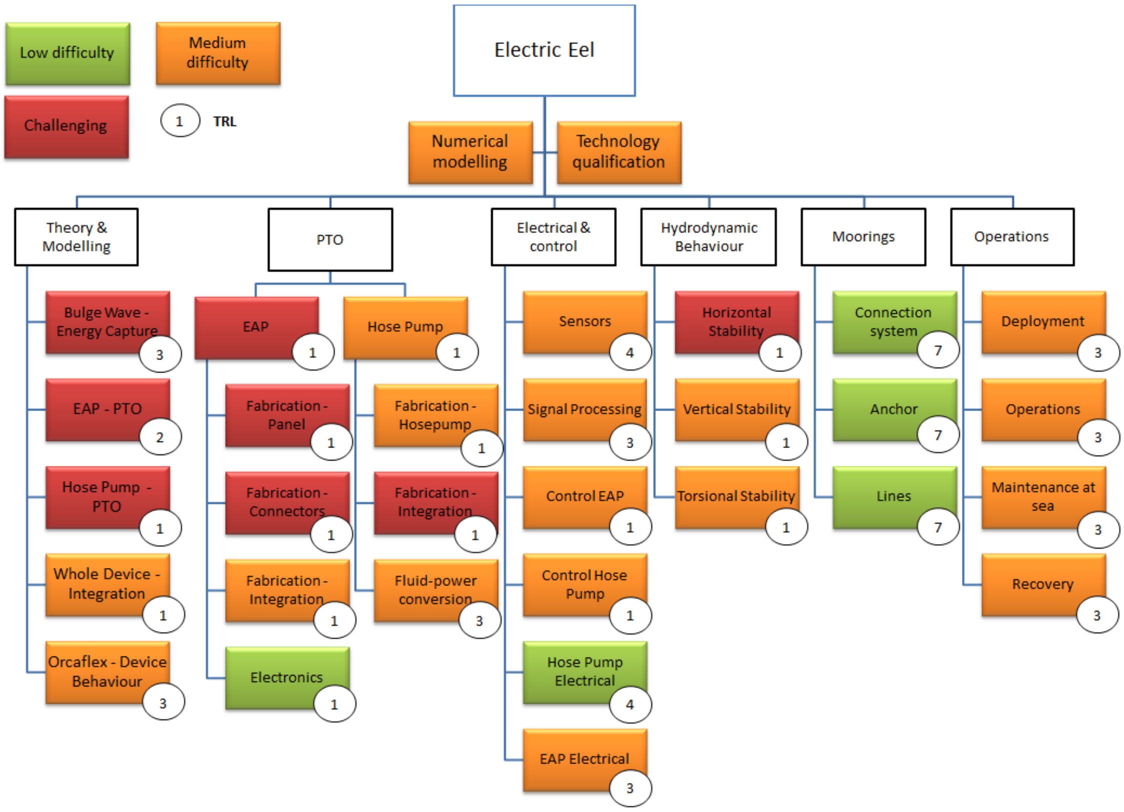

Figure 3: Sub-system TRL assessment

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 Electric Eel have already been developed for use in other applications, but the use in a wave energy converter is novel. More details and justification for the category assigned to each of the sub-systems is given in the following sections.

4.1 Elastomeric distensible tube

4.1.1 Development status

AWS Ocean have carried out initial sizing and simulation to determine the required stiffness and material properties of the distensible tube. Further work has been carried out by researchers on the Anaconda WEC which has developed knowledge on the bulge wave effect, however this is not available to AWS Ocean. Quotations were sourced for the purchase of material for a test device which allowed suppliers and manufacture techniques to be identified.

Embedding the PTO in the walls of the elastomeric tube is likely to be the most significant challenge to the manufacture of the device.

4.1.2 Technology categorisation

Category **4** – New technology (EPAM tube in marine environment) in new application (WEC).

4.1.3 Confidence levels

Whilst the application is a new one, similar technology (Anaconda & SBM Offshore) has been tested at scale prototype size already. This provides some confidence that the technology challenges can be overcome, albeit at small scale. Further work is required to establish confidence in our ability to achieve a full-scale system.

4.1.4 Development challenges

Unknowns within the design are:

- Fatigue life of elastomer
- Structural integrity under storm conditions
- Embedment of PTO in walls of tube
- Fabrication method
- Attachment to anchor connection point

4.2 Power take-off

4.2.1 Development status

EPAMs have been developed to a small commercial scale by AMI, now a division of Parker Hannifin and by Hyper Drive (Japan) who tested EPAMs in wave power applications and most relevantly, SBM Offshore who tank tested a distensible tube constructed from electro-active polymer. PolyWec is an ongoing FP7 funded project looking at the use of EPAMs in wave energy converters.

Initial sizing of an alternative hydraulic PTO has been carried out, there will be significant challenges in incorporating the required pipework into the distensible tube.

4.2.2 Technology categorisation

Category **4** – New technology in a new environment – The Electric Eel would represent a significant step up in scale for EPAM technology and a new environment in marine conditions

4.2.3 Confidence levels

The step up in scale and a new, challenging offshore environment mean that there are significant challenges to the development of an EPAM PTO incorporated into the distensible tube. It has been demonstrated at model scale in a wave tank by SBM Offshore however which gives confidence that a solution is possible. Against this is AWS Ocean's experience with researching fatigue in polymers for use in other wave energy applications. This work indicates that the issue is a non-trivial challenge.

4.2.4 Development challenges

Unknowns within the design are:

- Embedment of PTO in walls of distensible tube
- Significant step up in scale of EPAM – unknown whether it can handle the power
- Longevity of EPAM in harsh environment
- Fatigue life

4.3 Mooring system

4.3.1 Development status

The device is similar in form to the Pelamis WEC with similar functional requirements from the mooring system. Accordingly, the present assumption is that the Pelamis mooring design will be suitable. No further design has been carried out.

4.3.2 Technology categorisation

Category **1** – Proven technology in known application.

4.3.3 Confidence levels

Confidence is high that the Pelamis mooring system can be suitably adapted to suit the Electric Eel.

4.3.4 Development challenges

Unknowns within the design are:

- Final load conditions;

4.4 Electrical power system

4.4.1 Development status

No modelling of the electrical system has been carried out and no specification has been produced. EPAMs generate power at a high voltage (around 2-4 kV is common) which will bring some challenges. An electrical system associated with an hydraulic PTO is likely to be more straightforward.

4.4.2 Technology categorisation

Category **2** –customised but relatively common technology in an existing application (power control and distribution subsea).

4.4.3 Confidence levels

The electrical power system will make extensive use of standard components. Although some customisation is likely, confidence in delivery to TRL 9 is high (particularly if a hydraulic PTO is used).

4.4.4 Development challenges

Unknowns within the design are:

- Distributed power generation;
- High voltages generated by EPAM
- Power electronics cooling;
- Environmental protection;
- Fatigue in flexing cables;

4.5 Control systems

4.5.1 Development status

No modelling of the control system has been carried out and no specification has been produced. Active control of EMAPs and hydraulic PTOs has been demonstrated in the past although this configuration will bring new challenges and active control may not be possible.

4.5.2 Technology categorisation

Category **3** – advancements required on existing technology (control system technology) in an existing application (control of sub-sea equipment) but with novel features (distensible tube allows large deformations).

4.5.3 Confidence levels

Due to uncertainties in the feasibility of active control, confidence in delivery to TRL 9 is medium.

4.5.4 Development challenges

Unknowns within the design are:

- Algorithms for active control of Electric Eel;

5 Operations

5.1 Device construction

Construction of the Electric Eel at full scale has not been investigated.

At model scale, suppliers of elastomers were approached and potential materials, manufacturing techniques and costings were acquired. A supplier of EPAMs was approached but little progress was made due to licensing restrictions. It is unclear whether this restriction is still in place and other suppliers of EPAMs may now be available.

Handling of a large structure which includes both flexible and rigid elements may be challenging and require specialist equipment.

5.2 Deployment (e.g. Orkney location)

A detailed deployment plan for the Electric Eel has not yet been considered. As its dimensions and physical shape are likely to be similar to a Pelamis type device, it is expected that a similar deployment methodology will be developed.

Depending on final mass and design, large vessels may be required for anchor deployment however smaller work boats may be suitable for device deployment, recovery and maintenance work.

5.3 Operation & maintenance

5.3.1 Maintenance philosophy

Maintenance of the Electric Eel had not been considered in detail, however in common with many offshore WECs the design philosophy will likely be to avoid the need for frequent maintenance through simplification of systems and reduction in component count. Use of EAPs will significantly reduce the maintenance requirements of the PTO. 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 include:

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

5.3.2 Scheduled maintenance

A scheduled maintenance plan had not been developed for the Electric Eel. Typical tasks will include:

Planned at-sea maintenance

- Moorings inspection and service of connector;
- Cleaning of emergency pipe stabbings / control connectors;

Planned on-shore overhaul (5 year interval initially)

- PTO overhaul (if possible / appropriate);
- Replacement of corrosion protection anodes;
- Weld & plate thickness inspections;
- Patching or reinforcement of elastomer;
- Cleaning and re-painting as necessary;

5.3.3 Fault tolerance & sub-sea intervention

A detailed fault tolerant design had not been developed for the Electric Eel. Lessons learnt from previous WEC deployments, (for instance the Waveswing Mk1 installation in Portugal in 2004 and more recent Pelamis experience) will influence the fault tolerant design of the 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 internal fluid pressurisation, control system power and communication.

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 is set out in Appendix B.

6.2 TPL assessment summary

As the technology is very immature it is not possible to carry out a detailed TPL assessment. However the high-level criteria can be examined in order to obtain an indication of the likely TPL of a fully developed system. A more complex assessment could combine the potential performance of the system with the probability of overcoming the development challenges in that area. The initial assessment is presented in Table 1 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 is expected to be achieved safely. Recycling of polymers after decommissioning requires investigation.
Power absorption, conversion and delivery capability	8	High power absorption per unit volume of structure (best in class). High conversion efficiency through direct-drive actuator generator use.
System availability	7	High survivability potential and full shut-down possible. Performance critically dependant on fatigue life of polymer materials and durability of electrical system components.
Capital cost	7	Costs per unit volume are competitive with other offshore structures with potential for cost reduction through

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

		design and series production.
Lifecycle operational costs	5	Lifecycle costs are likely to be lower than for other WECS although this is critically dependant upon achieving acceptable overall device life.
Projected LCOE	6	Very initial estimates show LCOE at acceptable levels. Expected to reduce very significantly and rapidly if technology challenges can be met.
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: Electric Eel assessment of TPL potential

6.3 Justification of TPL assessment

6.3.1 Environmental and social acceptability

The Electric Eel is judged to have relatively low environmental impact due to its subsea location, however power density is relatively low meaning that greater sea-bed usage is required. The devices are flexible, however it is not yet known what construction facilities will be required and whether assembly can be carried out close to the deployment location. The devices do not have any inherent health & safety issues. Decommissioning of the large polymer structures may give rise to material disposal issues.

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 Electric Eel power absorption performance has been modelled using FEA techniques however a coupled hydro-dynamic model has not been developed. No tank tests have been carried out to validate performance levels. Uncertainty in power production therefore remains high, although reports from other projects (Anaconda) are that performance is likely to be acceptable.

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 has the potential to be high and contributes to a high TPL weighting.

6.3.3 System availability

The Electric Eel system has no moving parts however the primary failure mode is likely to be fatigue. This is expected to present issues in the EAP actuators, the electrodes and the interconnecting cables. Repair strategies have not yet been developed. Counter to this is the fact that the device is modular and hence tolerant of failure. Expectations are that if sufficiently long fatigue life can be achieved, then availability will be high.

Accordingly, it will be necessary to demonstrate long fatigue life (up to 15 years) for this element of the system to achieve a high TPL weighting.

6.3.4 Capital cost

The capital costs of the Electric Eel have only been assessed at a very high level to date, however the nature of the technology (roll-to-roll material processes) suggests that rapid cost reduction can be achieved through industrialisation and mass-production.

Accordingly, whilst there is uncertainty in this area, a weighting towards a higher TPL is considered reasonable.

6.3.5 Operational costs over the complete lifecycle

The Electric Eel itself does not have maintainable parts and hence maintenance activities will be limited to mooring inspections, removal of biofouling and maintenance of the surrounding infrastructure, as is common with all WECs.

Accordingly a high TPL weighting is considered reasonable for this area.

6.3.6 Projected LCOE

The LCOE for the Electric Eel has not been modelled in detail, however the initial LCOE values calculated in 2007 indicate that the technology can be competitive with other forms of renewable energy and that rapid reductions may be possible. Accordingly the TPL weighting is high.

7 Challenges to achieving commercial solution

7.1 General comment

The technology is at a very early stage of development and contains novel technology applied in a new and challenging environment. A staged program is required to develop this immature technology to a higher TRL, working through from lab tests of components and sub systems to wave tank tests and then on to scale prototype tests in a marine environment.

Some challenges faced will be common to other WECs (mooring, deployment, maintenance etc.) and learning can be gained from the experience of deploying and operating similar devices. At this early stage it is important to focus in the device specific challenges – for example the feasibility of the new technology to function cost effectively at full scale has to be proved.

7.2 General technical & engineering challenges

The Electric Eel is still at a very early stage of development. Significant challenges specific to the device lie in the following key areas:

- Commercial – identifying a supplier and manufacturing method for a full scale elastomer tube
- Commercial – Licensing issues around use of electroactive polymers in wave energy
- Commercial – Possible IP restrictions from Anaconda & SBM Offshore
- Technology – Finding a solution to embed the PTO in the tube wall
- Technology – Scale up of EAPs to large power and dimensions
- Technology – Complex numerical model required with coupled effects

7.3 Challenges to achieving utility scale

The device is not well enough understood to identify any particular challenges to achieving utility scale at this stage. In particular the parametric optimisation of LCOE has not been examined and accordingly it is not yet known if scaling up the device will provide fundamental economic challenges as is the case with some other device types (costs increasing with volume whilst power capture does not).

It is however suspected that costs of the Electric Eel are more likely to be proportional to the surface area (i.e. diameter) whereas power capture may be proportional to device cross-sectional area (i.e. diameter squared). If this is found to be the case then larger devices may be inherently more economic.

8 Technology development plan outline

A full technology roadmap has not yet been prepared however a package of work required to take the system and sub-systems to higher TRLs had been developed as follows:

1	**Macro Hydrodynamic Behaviour**
1.1	Write specifications for work package
1.2	Identify requirements for buoyancy as function of tube diameter
1.3	Originate solutions for horizontal stability (inc selective stiffness restraint, hydrodynamic surfaces, & pre strain provided by drag chute or mooring)
1.4	Originate solutions for rotational stability (e.g keel)
1.5	Originate mooring solution that enables weather vane & stability
1.6	Cost mooring solution as a function of displaced volume
2	**Micro Hydrodynamic Behaviour**
2.1	Write specifications for work package
2.2	Develop mathematical model of bulge wave creation to include damping, reflections, inertial effects
2.3	Modify mathematical model to account for floating mode excitation
2.4	Calculate strain – power relationship in steady state
2.5	CEL modelling to assess strain mode of floating excitation
2.6	CEL modelling to validate predictions of model
2.7	CEL modelling to validate bulge creation with mooring constraints
3	**Hydrodynamic Validation**
3.1	Write specifications for work package
3.2	Design experiment (inc prototype) to validate theory & CEL modelling
3.3	Identify suitable test tank
3.4	Procure prototype
3.5	Test prototype
4	**Extended EAP investigation**
4.1	Not used
4.2	Assess options for EAP & conductors inc fatigue, E limit, cost, suitability for fab, bonding & conductivity
4.3	Assess feasibility of EAP panel fabrication & identify processes
4.4	Identify circuit requirements & asses feasibility, losses & MTBF
4.5	Assess options for arc mitigation
4.6	Build dynamic model of EAP behaviour
4.7	Estimate EAP system costs/kW
5	**Extended Hose Pump Fabrication**
5.1	Patent hose pump composite panel smart structure
5.2	Assess feasibility of hose pump panel fabrication (inc manifolding & inserts) & identify processes
5.3	Identify hydraulic circuit requirements & asses feasibility, losses & MBTF
5.4	Build dynamic model of hose pump behaviour
5.5	Estimate hose pump costs/kW
6	**Whole device Fabrication**

6.1	Identify suitable materials for strain, fabrication, fatigue & UV degradation requirements
6.2	Assess feasibility of large scale 3D fabrication & identify processes – hose pump & EAP
6.3	Assess feasibility of modular construction and originate concept
6.4	Estimate device fabrication costs/m^3
7	**Device Performance Assessment**
7.1	Predict capacity factors & device ratings as a function of diameter & length assuming polychromatic seas for passive & adaptive devices
7.2	Estimate total device costs as a function of rated power
7.3	Assess economic performance as function of capacity factor & rated power using updated cost info for passive & adaptive devices
7.4	Quantify benefit of AWS IP over Anaconda

Table 2: Initial technology development plan

9 Conclusions

The Electric Eel wave energy converter is a promising solution to harnessing power from the waves and offers significant improvements over similar devices along with potential for cost reduction. There are significant challenges to the realisation of a full size WEC particularly around the scaling up of a PTO which has only been proven at a very small scale.

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