# Anaconda Novel WEC

## *WES Novel Wave Energy Converter*
## *Stage 2 Project*

## *Public Report*

**Checkmate SeaEnergy Ltd.**

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# 1 Project Introduction

Following completion of Stage 1 of the Wave Energy Scotland (WES) Novel Wave Energy Converter (NWEC) Project in January 2017, CSL was awarded further funding to progress the development of the Anaconda technology as part of Stage 2. Stage 2 included the undertaking of a series of laboratory tests, numerical modelling activities, and concept development of a full-scale configuration of the technology (originally designated the “Mk1”). The Anaconda Mk1 WEC adopted a closed loop hydro-elastic PTO, whereby power smoothing is realised by temporarily storing power peaks in specially configured hydro-elastic accumulators before conversion to electrical power by creating smoother hydraulic power flow through a turbine between high pressure and low-pressure accumulators. The Stage 2 engineering assessment included further testing of this technology configuration as well as a controllable linear piston PTO. This new experimental linear PTO allowed more control of the bulge tube interface to improve understanding of the ultimate absorption potential of the Anaconda bulge tube technology. This work also helped to pave the way for future “MkX” variants of the system, targeting improved economic potential.

The project participants are shown in Figure 1.

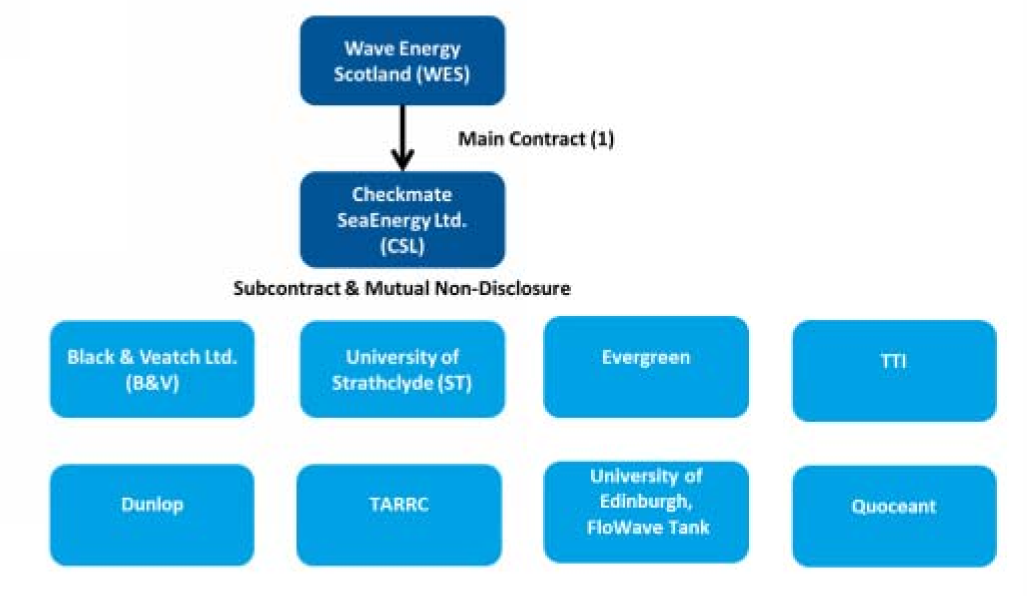

Figure 1: Project Commercial Structure

## 2 Description of Project Technology

The wave energy absorption principle of Anaconda is based on the response of a water-filled distensible "bulge tube" placed within an incident ocean wave field. The tube sits just below the water surface and is aligned approximately perpendicular to the oncoming wave front. The waves excite a propagating "bulge-wave" modal response of the tube. Given certain elastic properties, the result is a broad-banded, low impedance, omni-modal oscillation that delivers a highly-amplified oscillatory flow potential at the tube's stern. A PTO Module at the tube's stern converts the available flow potential to useful power. Uniquely for WEC oscillators, the reactive properties of the oscillator are distributed throughout the tube as a "continuum". This means there is a strong de-coupling between the power conversion forces at the PTO and the reactive forces within the bulge-tube continuum that sustain the fundamental wave energy absorption. This means that the PTO requires no reactive control forces or advanced damping strategies to maintain good power conversion.

The Anaconda bulge-tube hydro-elastic solution couples power performance and survivability in both extreme conditions and operational conditions. The governing design parameters of the bulge-wave tube's dynamic response to wave excitation influence this balance between cost, power performance and survivability. Determining how to select the design parameters to address this balance and demonstrate economic potential was a key target outcome of the Stage 1 and 2 developments.

The Anaconda is a radical change from other families of WEC devices, with potential for step-change improvements in several aspects that impact overall LCOE:

- A key advantage is that at the point of conversion, only relatively simple damping strategies are required to convert the available power, with no need for more complicated control strategies or reactive forces.
- The scalability of the bulge tube lends itself to a modularisation of the bulge tube function as well as adaptability to the full-scale resource at any power rating, including for smaller micro-generation applications.
- A self-referencing primary absorber based on flexible materials avoids the need for any articulated joints, reference bodies and/or end stops associated with rigid wave activated bodies. This offers potential step changes in reliability and survivability.
- The low draft horizontal orientation permits the use of new installation and maintenance principles for marine operations offering potentially radical changes to installation and O&M costs.
- There is potential for a step change in structural weights and material costs, especially given the future innovation potential in the primary bulge tube design, with "alternative distensibility" solutions at full-scale that can be engineered from any energy storage material (including steel & plastics).
- There is a drastic reduction in the criticality of structural failure modes of the primary absorber, relative to large steel structural failures.

The novelty of the Anaconda technology presents substantial opportunities to reduce LCOE of wave energy technology through the significant amount of learning which can be achieved during the continued development and understanding of this concept. This contrasts with rigid body structures where there are well-established analysis, design and construction techniques but often more limited learning potential in delivering on a pathway to the WES target unit cost of energy.

# 3 Scope of Work

The scope of work for Stage 2 project was informed by the Stage 1 outcomes. The scope was mainly split in two phases, the concept design of a full-scale device (now designated Mk2) and Front-End Engineering Design of a 1:4 scale prototype (now designated Mk2S). With regards the main technical points within these streams, the behaviour of the rubber, its influence on performance and the manufacturing issues were priorities within the work programme. Furthermore, the PTO arrangements were investigated in far more detail than in Stage 1.

The specific scope of the NWEC2 work with the respective WPs is detailed below:

- WP2 Mk1 / Mk2 Concept Design: System Engineering Management

  The objective of this WP was to manage interfaces among subsystems and to record risks and opportunities. This WP produced basis of design and design statements for Mk1. Furthermore, this WP kept a live Systems Engineering workbook containing a novelty assessment, risk assessment and interface assessment and managed the iteration of the concept to the current Mk2.

- WP3: Rubber Structural Engineering:

  The objective of WP3 was to apply the experience from large-scale rubber manufacturing in existing industries to refine the concepts for the critical rubber components of the Anaconda technology. This WP carried out some rubber analysis in terms of the optimum formulation for Mk1, and also a manufacturing study highlighting the issues and the procedures that would be utilised to manufacture full-scale Mk2 hardware and the components for a scaled sea-going Mk2S prototype.

- WP4: Subsystem Concept Design

  The objective of WP4 was to develop conceptual designs of the various subsystems of the full-scale Anaconda configuration to a sufficient level to confirm feasibility and to support predictions of budgetary costs. This produced concept designs of the primary tube, the PTO, the hull and the moorings.

- WP5: Lifecycle Design Refinement

  The objective of this WP was to firstly develop a preferred assembly and installation strategy to increase confidence that the baseline configuration can be safely executed at the proposed deployment site and secondly undertake an LCoE analysis.

- WP6: Prototype FEED: System Engineering Management & Test Plan

  The objective of this WP was to manage interfaces among subsystems and to record risks and opportunities. This WP produced basis of design and design statements for a seagoing prototype, designated Mk2S. Furthermore, this WP kept a live Systems Engineering workbook containing a novelty assessment, risk assessment and interface assessment. Additionally, this WP also prepared the qualification activities needed for Stage 3.

- WP7: Rubber Structural Engineering – Mk2S FEED

  The objective of WP7 was to complete FEED of the rubber components (for the sub-scale, sea-going Mk2S prototype to be delivered to the test site (Scapa Flow, EMEC).

- WP8: Mk2S Subsystem - FEED

  The objective of WP8 was to develop FEED level designs of the various subsystems of the sub-scale Mk2S prototype to be taken forward to Stage 3.

- WP9: Mk2S Operations Planning & Test Plan

  The objective of WP9 was to develop plans and procedures for marine operations required to install, operate and decommission the Mk2S prototype.

- WP10: Operational & Survival tank testing

The objective of this WP was to test the 1:25 model of the Anaconda baseline configuration in representative scaled ocean conditions of the reference site, South Uist.

- WP11: Controllable PTO tank testing & Numerical Model validation

  The objective of this WP was to test the 1:25 model tank testing of the Anaconda configuration with an alternative PTO solution in representative scaled ocean conditions of the reference site, South Uist. These tests were performed in Glasgow.

Addressing some of the findings during NWEC2 led to a supplementary programme of work that updated the concept and FEED to the Anaconda Mk2, which is a configuration with a linear PTO. This included an additional tank testing campaign at Lir in Cork, rubber compound research by TARRC and an engineering definition of the new PTO arrangement.

# 4 Project Achievements

## 4.1 Main achievements

Stage2 development saw extensive laboratory testing successfully completed over 3 tank test campaigns and the use of that data to underpin:

(a) Extensive iterative concept engineering to develop a technology configuration that can achieve the step change economic objective demanded of the WES programme;

(b) A Front-End Engineering Design (FEED) of a sea-going test platform that takes the technology forward in Stage 3;

(c) Economic projections showing a commercial path to delivering affordable utility scale electricity.

Throughout Stage 2 laboratory testing, the experimental team have observed consistent, broad-banded absorbed power that sustains excellent energy absorption across the range of wave frequencies. It has been relatively insensitive to the damping strategy deployed. During NWEC2, the team applied a fully-controllable linear actuator PTO.

Following a "Preliminary Design Review" (PDR) in May 2018, which included WES and other external observers, the decision was made to pursue a revised Mk2 technology architecture based on these test results. The principle Mk2 updates relate to the adoption of a more streamlined and cost-effective linear PTO module to be adopted in the commercial baseline. Supplementary testing and concept design work was undertaken from June to August 2018 to de-risk and develop the Mk2 concept architecture as well as address other concept updates. The fundamental tube behaviour and scalability of projected performance is much better understood and has identified a commercialisation path towards long term economic outcomes. Checkmate has identified 2 commercial technology configurations on the route to commercialisation.

Firstly, the Mk2US "Utility Scale" variant intended to generate bulk renewable electricity for grid dispatch maintains a target rating of 1MW.

Mk2EA – A commercial configuration of a small device targeting power for offshore embedded generation or island communities. The aim is to compete with diesel generation in remote ocean locations. The Mk2EA commercial product will aim to access a stepping stone market for Anaconda technology. The intention will be to leverage existing large-scale rubber manufacturing capacity to keep CAPEX low and to go to series manufacture on smaller units to accelerate learning.

To support the concept updates and initiate the commercialisation plan, Front End Engineering Design (FEED) was completed for a sub-scale Mk2S prototype, proposed to be deployed at sea under WES Stage 3. The prototype "Anaconda Mk2S" designates a sea-going test platform, proposed for deployment at Scapa Flow for 1:4 (to 1:4.5) scale tests during NWEC3. It is designed around three subsystems:

(a) PTO Module: A linear PTO module integrated in a steel hull. The module is very similar to the NWEC2 tank test PTO in operating principle. It is a highly adaptable experimental platform to facilitate operations across a range of scales including 1:4 scale operations, while also similar to full-scale intent.

(b) Tether Systems: This includes mooring lines, surface buoy, horizontal hawser, nose-cone and an "internal tether" within the tube. It provides survival integrity and moors the PTO module completely independently of the bulge tube.

(c) The Bulge Tube: The PTO module and tether system collectively provide a high-integrity platform, onto which the high novelty bulge tube elements can be deployed and safely tested. Stage 2 gives confidence that a 1:4 scale rubber tube can provide a resilient, affordable and manufacturable test. The Mk2S bulge tube utilises conveyer belt manufacturing capability from Fenner/Dunlop, a subsidiary of Michelin Group.

The project has delivered an excellent design for a 1:4 test platform that Froude scales to currently targeted Mk2 concept. It lends itself to further adaptation for small full-scale devices and the validation of small “modular” full scale hardware that could be aggregated to form utility scale devices as an alternative scaling strategy.

# 5 Summary of Performance against Target Outcome Metrics

A short summary of the outcome of Stage 2 work in terms of a subset of the target outcome metrics follows.

## 5.1 Affordability – Capex

Outcome following completion of Stage 2 activities:

| | **Target** | **Mk1C** | **Mk2** |
|---|---|---|---|
| **P50 CAPEX (FOAK)** | £7.5m/MW | £12.5m/MW | £7.3m/MW |
| **Prototype CAPEX** | <£1m | N/A | £500k |

During NWEC2 the concept engineering was advanced considerably, and the target outcomes were rigorously assessed against resulting metrics during the project and particularly at the PDR. Specific challenges did emerge in the Mk1 configuration of the technology that was taken forward from Stage 1 and the principle way these manifested themselves was in an escalation of CAPEX. Two such key challenges were:

(a) PTO Hull CAPEX:

A detailed assessment of the Mk1 PTO and power conversion solution showed some specific challenges with respect to CAPEX. An updated Mk2 PTO design resulted in a £2.3m saving in FOAK CAPEX over the reference Mk1C, with additional consequential savings in Assembly operational costs (elimination of rubber to steel joints and general scale for handling) and mooring costs (due to a reduced drag profile and displacement).

(b) Rubber tube joint feasibility & CAPEX implications:

There is an unavoidable material cost in providing the elastic energy capacity required to achieve an elastic tube of target distensibility and facilitating the required “bulge capacity” about the equilibrium state for wave absorption (i.e. such that ULS and FLS design conditions are met). The Design Envelope for Bulge Tubes was identified in Stage 1 in which a solution to achieve cost-effective bulge tube design depended on being able to join rubber panels to fabric panels. NWEC2 concept engineering shows that such joints were too high risk for current large-scale rubber manufacturers and an acceptable near-term joint solution was not found. This led to applying jointless “All Rubber” tubes for near term solutions, which have now also been adopted for the current baseline Mk2US FOAK design. This results in an inherently resilient, long-life, tube but of much higher rubber content and CAPEX for the full-scale configuration. (In effect, the elastic capacity of the tube is underutilised). Supplementary stage 2 work successfully demonstrate the means to alleviate these cost escalations over the near and longer term.

Other CAPEX challenges encountered related to concept mooring costs and assembly and operational costs. These were resolved in follow up assessment of the Mk2 configuration where the changes to the tube and PTO concept design precipitated further savings as a result of reductions in overall displacement, structural mass and large assembly interfaces.

## *5.2 Affordability – Opex*

| Outcome following completion of Stage 2 activities: | | | |
|---|---|---|---|
| | **Target** | **Mk1C** | **Mk2** |
| **First Array (Utility Scale)** | £356k per MW pa | £390k (per 750 kW pa) | £360k (per MW pa) |

A detailed Operational Model was undertaken in NWEC2. Checkmate accepts that OPEX and Availability are crucial to control and this is a clear focus in design architecture and design life strategies for rubber components.

## *5.3 Performance – Rated Capacity*

| Outcome following completion of Stage 2 activities: | | | |
|---|---|---|---|
| | **Target** | **Mk1C** | **Mk2** |
| **First Array Rating / Capacity Factor** | 1MW / 30% | 750kW / 32% | 1000kW / 27% |
| **Mk2S Prototype (1:4)** | TBD | N/A | 8 kW |

The performance assumed in all models is based only on measured data from 1:25 tank tests and does not include any numerical extrapolation. Target Utility Scale ratings were confirmed, though the rating also depends on the specific power conversion strategy employed and the chosen definition of nameplate rating.

The device rating for Mk2S is targeted to be up to 1:4 scale at Scapa flow and this is the design basis for FEED, though the wave climate may facilitate better testing at a scale such as 1:4.5, to be selected on a detailed assessment of the resource.

## *5.4 Performance – Power Conversion Efficiency*

| Outcome following completion of Stage 2 activities: | | | |
|---|---|---|---|
| | **Target** | **Mk1C** | **Mk2B** |
| **First Array Conversion Efficiency** | 73%-82% | 77% | 70% (but greater absorption potential) |
| **Mean Electrical** | N/A | 260kW (34% of 0.75MW) | 270kW (27% of 1MW) |

## *5.5 Other - Manufacturability*

| Outcome following completion of Stage 2 activities: | | | |
|---|---|---|---|
| | **Target** | **Mk2S (1:4 Scale)** | **Mk2 Full Scale** |
| **Rubber to Rubber Joints:** | Joint solution identified | Re-design to All Rubber successful | Re-design to All Rubber successful |

NWEC engineering team included Black & Veatch working with Rubber Consultants TARRC and conveyor belt manufacturer Fenner/Dunlop, a subsidiary of Michelin Group. A near-term means to address the rubber tube joint manufacturability issue was identified. Full-scale diameter tube manufacturing is conceptually feasible, but the existing supply chain does not exist and one-off investments make a direct transition to manufacturing such hardware unattractive. The improved understanding of the scalability of tubes has identified alternative commercialisation routes that leverage existing manufacturing capacity and potentially allow a modular approach to providing the utility scale bulge tube hardware. This will need verification in future developments.

## 5.6 Other - Scaleability

This is one area where technology understanding has been modified and improved greatly:

- The manufacturability of single full-scale rubber tubes of 1MW is technically feasibly but on assessment of operational practicalities (including the manufacturing processes required) and port infrastructure requirements, the scale of the primary tube component makes the development path step directly to a 1MW variant based on a single large rubber tube unlikely.
- Stage 2 developments, in particular the assessment of cost-effective all rubber tubes showed that tuning to full scale waves is independent of tube diameter. This has important opportunities in terms of the scalability and commercial planning of the technology.
- The other observation is that because of the nature of tube scaling, Anaconda lends itself very well to smaller devices, tuned to the full-scale resource but applied in early adopter markets for offshore embedded power demand or island markets. Such configurations may be in the region of 100-200kW

With this scalability opportunity in focus, the Mk2S prototype has been developed such that the PTO module is geometrically oversized (in order to present the minimum viable scale for operability and human access, but also to have the best possible chance to be upgraded after Stage 3 tests for larger scale testing).

## 5.7 Other - Controllability

Control for Performance:

- Mk2 tests with a controllable piston have confirmed that the performance is far less sensitive to PTO control forces than typical WECs. A PTO at the bulge tube’s end, can convert a portion of the available flow potential to useful power, with any “rejected” power simply resulting in bulge-wave reflection, which is then re-radiated to the sea. There is a de-coupling between the power conversion forces at the point of energy conversion and the reactive forces that are required to sustain the oscillatory response for fundamental wave absorption. Throughout recent development testing, the Anaconda development team have consistently observed that power conversion is insensitive to the damping strategy deployed at the point of conversion and requires no reactive control forces to sustain upstream energy absorption of the bulge tube. This has emerged to be a key advantage over state of the art wave energy conversion in terms of the duty placed on the PTO.

# 6 Recommendations for Further Work

Stage 2 has delivered TRL4 readiness for the technology. It is recommended that a Stage 3 test program is now undertaken to deliver TRL5 and TRL6 objectives. This program of work should include a test and qualification programme using subsystem bench testing leading to full system sea-trials of the Mk2S hardware, those tests targeted at mitigating the technology risks identified for the Anaconda Mk2 system. Summary objectives should be:

- Rubber & scaling
    - Rubber development and testing should demonstrate and validate the scalability understanding developed in Stage 2. This spans the unique scaling characteristics for performance that underpins the commercialisation plan, including constraints associated with rubber fatigue and aneurysm.
    - Manufacturing tests of the target rubber compound and using the intended large-scale manufacturing solution should be carried out on sample lengths of 1:8 to 1:4 scale tube section. Static inflation tests should validate the geometric stability in advance of device integration.
    - The general operational resilience of such rubber structures should be tested with reference to sea-trials and realistic operational handling of a 1:4 scale rubber bulge tube on a platform that does not depend on the tube for mechanical integrity.
    - Further numerical / analytical assessments using the tools developed in Stage 2, supported possibly by interim scale (circa 1:10) tank tests should be used to validate the potential of the “Early Adopter” market device scales corresponding to 100kW – 200kW ratings.
- PTO
    - A linear PTO module of a design that is representative of full-scale intent (as per FEED) should be detail designed and assembled for validation tests.
    - Extensive dry commissioning tests of the full assembly in a controlled environment should be undertaken prior to in-sea deployment. This testing may include actuating the PTO utilising the control algorithms. Prior to this there may be component specific testing, if required.
- Mooring and Tether Systems:
    - Mooring model validation against tank test: Building on the strong understanding of mooring and internal tether loads now captured in Stage 2, the optimal means to deliver this functionality should be devised and tested in the Mk2S prototype.

# 7 Communications and Publicity Activity

Publicity for the Anaconda device in the WES Novel WEC programme has taken the form of press releases and updating of the CSL website (http://www.checkmateukseaenergy.com/) as well as attendance and presentations at the WES Annual Conferences.

# 8 *References*

CSL website for latest project/technology status updates:

- http://www.checkmateukseaenergy.com/

Publicly available papers:

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