MARINE AUTOMATICALLY STOWABLE & INFLATABLE VOLUME (MASIV)

WES Novel Wave Energy Converter Stage 1 Project Public Report

Quoceant

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

Wave Energy Converters (WECs) must be both robust, have good survivability characteristics, and produce sufficient average yield to deliver attractive economic performance. Many different WEC concepts, forms and engineering solutions have been proposed to deliver against the two commonly conflicting requirements of performance and survivability but the compromise between the two remains a major barrier to improved cost of energy. The novel WEC concept developed in this project is intended to break this fundamental conflict between performance and survivability by introducing the ability to substantially change the machine hull volume on command; in the same way that sailing ships reef their sails to deliver both speed and survivability, selectable hull volume change allows a WEC to grow substantially to absorb much more power during most of the year, while reverting to a smaller, robustly survivable form when the conditions become extreme.

In short, the technology being developed provides the economics of an otherwise un-survivable machine with the survivability of an otherwise uneconomic machine. Levelised Cost of Energy reductions of up to 50% are possible on a line-absorber, but the innovation is applicable to multiple classes of WECs. The particular advantages of this invention in marine renewables have led to this innovation being dubbed MASIV, or Marine Automatically Stowable and Inflatable Volume.

The Quoceant team are specialists in marine energy and technology innovation. They, and the associated partners invovled, brought experience, knowledge and capability to the project to ensure efficient delivery. The Quoceant team previously worked together on the Pelamis Wave Power project and have amassed a combined experience of nearly 150 years in the marine sector. Quoceant formed two years ago and provide independent, expert engineering consultancy services to a range of organisations working in the wave, tidal and wider marine energy sector. They brings the broad multidisciplinary experience and have direct experience of load bearing pressure loaded fabric design. They also have extensive experience designing, detailing and manufacturing a wide range of attachment systems, mechanical details, sealing and inflation systems, all of which add value to this project; the unrivalled experience of the project team ensured the project was delivered efficiently with maximum benefit to all parties.

The exciting motivation for this innovation was that it has the potential to dramatically reduce LCoE. A number of ways of engineering a system to provide the desired gross hull volume change were conceived and evaluated prior to the start of the project. The most promising of these used inflatable membranes to cost effectively provide a gross increase in volume around a rigid load bearing core. Based on this concept, the project set out to prove the feasibility of an engineered system using state of the art tools. The well-researched articulated line-absorber configuration was used as a robust case study to quantify the strong reduction in Levelized Cost of Energy (LCoE), taking into account integrated capital cost, impact on annual average yield, operational costs and availability. It has been confirmed that significant and transformative LCoE reductions, achieving the project target of 25-50%, are deliverable. As well as demonstrating a step change in opening LCoE figure, it is also reasonable to assume that this innovation will reduce longer term asymptotes and floor costs. The innovation therefore has the potential to massively reduce the 'cost to commercialise' or 'cost to converge' for a wide range of WEC configurations.

1.2 Description of Project Technology

Quoceant are delivering the major benefits of a changeable volume hull through the development of MASIV, of marine automatically stowable and inflatable volumes. These large, controllable, inflatable, and stowable volumes have benefits in terms of each of the 4 critical metrics for WECs:

- **Performance** (power capture) is enhanced through creation of a significantly larger hull volume;
- **Survivability** is drastically improved via reduction of peak loads and motions (in deflated state);
- **Affordability**: better matching of extreme and normal loads enables increased structural efficiency and realisation of cost reductions;
- **Availability**: de-risking operations enables O&M strategy updates and availability improvements.

The novel WEC concept investigated during this stage 1 WES funded project was an articulated line-absorber equipped with the MASIV system. The stark differences in WEC behaviour in the same waves, under appropriate control conditions for the situation, is obvious in the stills from synchronised videos below. The high-volume, inflated WEC (left) has exaggerated response characteristics, and hence far higher power capture, than the low-volume, deflated WEC (right) with less movement and better survivability characteristics. Steep waves have previously been shown to be the most severe in terms of survivability for a line absorber style WEC but again, as the second stills show, the more benign motion of the LV model is clear; it dives through the steep, breaking, wave far more readily. This means that it doesn't leap out of the front of the wave and subsequently slam down. Again, this is a great result in terms of survivability.

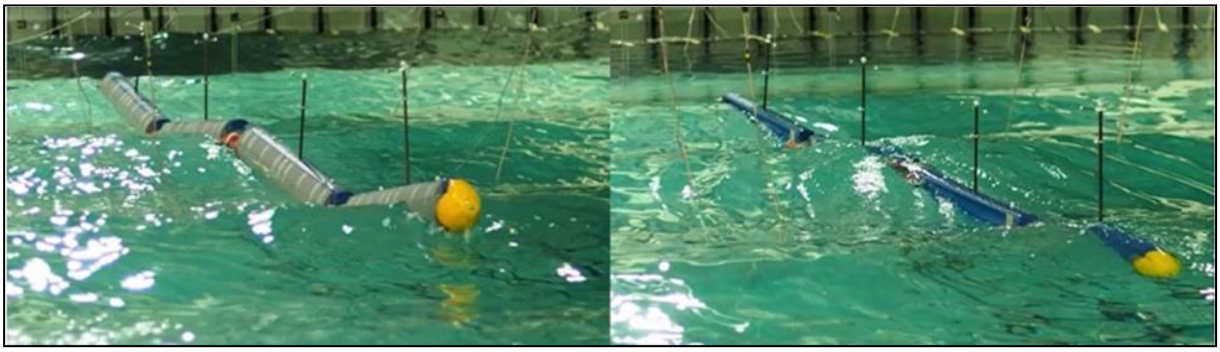

Figure 1: Captures from synchronised video of HV & LV models in WES standardised sea state (R11, Hs = 4.5m, Te = 7.5s)

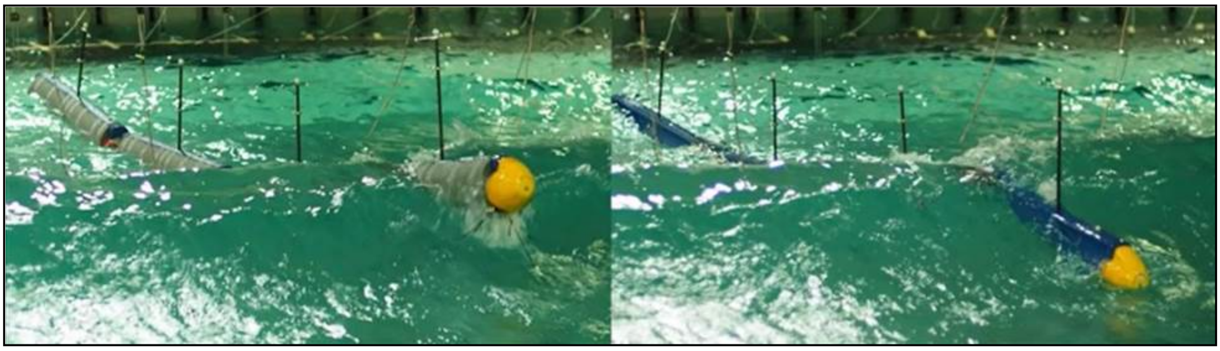

Figure 2: Captures from synchronised video of HV & LV models in Quoceant defined 'steep' sea state at wave steepness limit (Hs = 7.5m, Te = 9s). Capture from extreme wave section (Hmax = 14.3m)

A line absorber has many inherent benefits for further development as a wave energy convertor:

- It's streamlined shape, small frontal area and long length ensures loads are minimised;

- It is self-referencing, meaning it does not react against its moorings to generate power but instead reacts against itself; this allows the mooring system to remain slack in all but the most extreme sea conditions.
- Line absorbers have inherently higher power capture potential compared to many other WEC concepts;
- They naturally weathervanes to face prevailing sea conditions ensuring its inherently high potential capture width can be realised in the vast majority of conditions,
- A line absorber has good core survivability due to curvature limiting of waves.

The line absorber technology has already been advanced TRL and decent TPL during the Pelamis development programme, however, the inescapable fact is that the drive to improve power performance leads to increasing volume but this also compromises the self-limiting characteristics of the device. This project tackled that compromise through innovation to deliver more optimally engineered solutions and a lower cost of energy.

1.3 Scope of Work

The primary focus of work packages 1-3 was to establish the basic viability of the concepts and the relative merit of a range of potential embodiments. All embodiments of the MASIV concept considered were shown to have merit and to be feasible. 2D and 3D finite element analysis (FEA) work was undertaken alongside preliminary comparative 3D structural FE analysis. Behaviour of the inflated volume during submergence and deflation was studied enabling preliminary fabric tension and stress values to be computed and inflation pressure to be determined. This enabled an appraisal of the market with respect to possible fabric options and costs. 3D FEA of the inflated volume's behaviour when subjected to impact loads was also completed. The different embodiments were then comparatively assessed and a reference design for ongoing physical modelling defined.

In the next stage of the project, work packages 4 and 5, two separate physical modelling programs were undertaken, namely performance testing and functional testing. The functional testing element of the project was designed to demonstrate feasible and practical mechanisms of operation, to investigate the stability during submersion and investigate robustness during the transition between the inflated and deflated states. The performance impact of the additional volume was investigated by conducting performance tests with a representative line absorber in the FloWave test tank. These tests allow comparison between the motion and performance characteristics of the inflated and deflated hull forms. Physical performance tests also enable verification of the computer simulation programmes and confirmation of the validity of the model. Once validated, the numerical model was then used to extrapolate overall yield improvements for a broader range of annualised conditions.

The projects latter work package dealt drew together the results from both the performance and functional tests and earlier engineering investigations. More comprehensive systems design and costing exercises were undertaken. A range of different yield forecasts were made for different configurations and embodiments of WEC allowing a robust Levelised Cost of Energy (LCoE) model to be created. Using this model, the improvements in LCoE possible from the inclusion of MASIV into a line-absorber were calculated allowing comparisons to a baseline line-absorber case. The improvements enabled can therefore be expressed in a number of accessible and familiar metrics.

1.4 Project Achievements

1.4.1 Viability Studies

The primary focus at the beginning of the stage 1 project was to establish the basic viability of the concepts and the relative merit of a range of potential embodiments. To achieve this, a series of interrelated engineering studies were conducted that enabled the original concepts to be developed and iterated. Each study was aimed at characterising or mitigating risks identified in the risk register, or confirming that requirements defined in the functional specification could be achieved. The main analysis activities were 2D FE analysis to determine material load requirement and swept volume efficiency, 3D FE analysis to investigate end effects and behaviour during deflation, and some simple structural FE analysis to illustrate differences in core hull behaviour.

Two main inflatable concepts were considered and developed theoretically and conceptually. Sufficient work was completed to ascertain that each of the designs considered are reasonable, feasible and have engineering merit. The work undertaken provided the basis for functional testing and helped determine the priorities and objectives for these tests. Crucially, all systems investigated involve pressures in the inflatable volume well within practical limits and loads in the flexible membrane are within the capabilities of materials that are currently available and on the market. No technical barriers to further development of the concept were identified.

The conclusions of the work undertaken in relation to the functional specification for the system are:

- **Volume Change:** A volume change nearing 2:1 is eminently possible. The current embodiment of the MASIV system targets a ratio of 1.8:1 to simplify the ballasting requirements.
- **Stowing/Inflating:** Finite element analysis indicates that reliable, passive inflation and deflation can be achieved with either concept being considered.
- **Stowability:** All concepts stow neatly against the base hull structure after deflation.
- **Loss Swept Volume:** The loss swept volume (the volume that the inflated structure loses under external pressure loading and wave action) is minimal.
- **Loading:** Flexible membrane loads for all concepts are well within the capabilities of already available and manufactured materials.
- **Attachment points:** Simple and maintenance friendly clamping of the membrane to the hull of the WEC is appropriate and achievable.
- **Impact Energy Abs.:** Impact tests showed that the system is capable of absorbing significant energy with ease which mitigates survivability risks of the system itself, but critically mitigates against impact with the rigid hull as well.

Comparison of the two main concepts being considered resulted in the selection of the most promising concept for further development; a large air volume, axially aligned along the line absorber's tube segments that inflates to a convex shape on either side of the hull. A controllable inflation/deflation system within the hull of the WEC enables volume of the WEC to be controlled depending on conditions. When conditions are too extreme, this additional volume can be controlled and deflated to conform to a concave rigid hull of equivalent perimeter to the inflated form. Not only does this system confer significant advantages in terms of performance (when inflated) and survivability (when deflated), but the alternative, deeper hull shape can also deliver structural efficiencies to the WEC design.

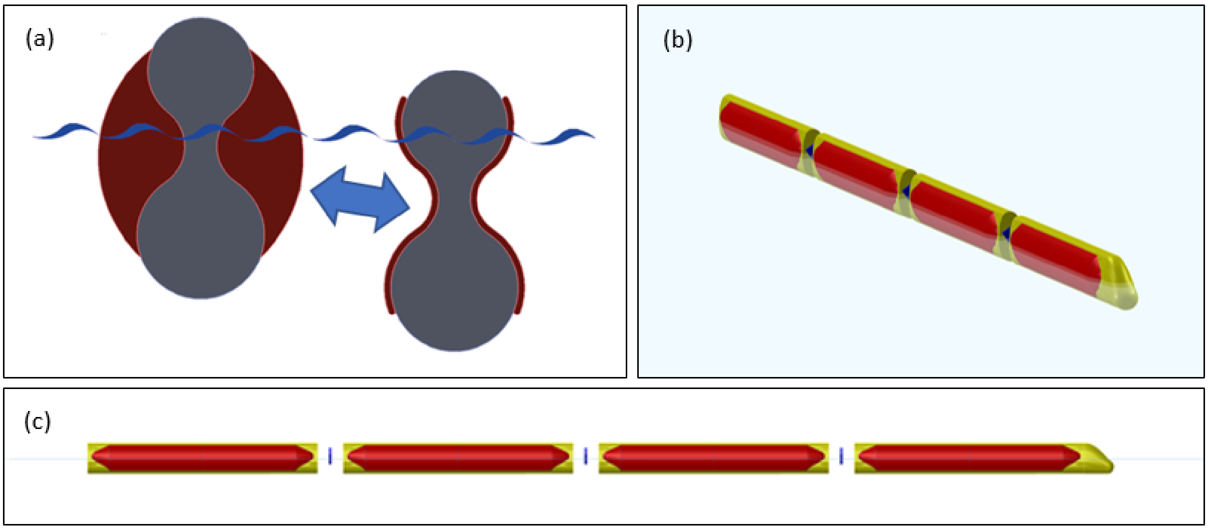

Figure 3: (a) Cross-sectional concept illustration of MASIV in inflated and deflated state, (b) & (c) Conceptual illustration of MASIV inflatable structures on side of tube sections.

1.4.2 System Design & Specification

Top-level engineering design has been completed for the inflatable structures including specification of the fabric requirements and confirmation with an industrial supplier that fabrics that meet this specification are available. The most cost effective solution is expected to be a hybrid fabric with a high strength textile core, neoprene rubber coating to provide bulk, and an outer Hyperlon™ coating to provide environmental resistance. Similar fabrics are already used widely and successfully within the marine industry in rigid inflatable boats and in fender technology.

Figure 4 (left-to-right): Layered construction of fabric material commonly used in many marine applications already available on the market, example use in rigid inflatable boat, example use in quayside fender systems.

System specification and design of the inflation/deflation pneumatic system has also been completed. No technical barriers to system development were identified. An industry wide search of applicable technology led to selection of the appropriate main compressor systems, the associated air intakes, filters, mist eliminators, pipework and valves; all been selected from available off-the-shelf technology.

Structural implications, required adaptations and options were also considered and costed using Quoceant's extensive experience and indicative metrics. The deeper section depth of the MASIV core hull for a given cross sectional area and associated structural efficiencies, in conjunction with the expected smaller loading regime, both confer structural advantages to a line-absorber incorporating the MASIV system. However, this is somewhat offset by the increased complexity of the hull design. None-the-less, structural fabrication costs are not expected to increase substantially.

1.4.3 Practical Testing

Following on from the selection of a specific concept embodiment, a reference design for onward practical testing was developed. The practical testing development of the project was split into two streams:

Functional Testing: These tests were designed to demonstrate feasible and practical mechanisms of operation and to establish stability throughout submersion and during transition between the inflated and deflated states. They also enabled practical demonstration of the premise that the inflated structure is broadly similar to a rigid volume and to estimate 'lost swept volume' effects and validate simulations.

Performance Testing: The performance impact of the additional volume was investigated with a representative line absorber model in the FloWAVE test tank. These tests allowed comparison between the motion and performance characteristics of the inflated and deflated hull forms.

1.4.3.1 Functional Testing Conclusions

Tests were completed on several different materials with different sealing techniques used giving Quoceant much experience with different elements of flexible membrane technology. Comparisons between membrane profiles measured during the functional tests and those outputted from finite element analysis showed excellent agreement thus validating the finite element analysis results and confirming that the loss swept volume can be kept within required limits and that membrane loads are well within the capabilities of readily available marine materials.

Behaviour of the membrane during inflation and deflation was very encouraging. The membrane was well controlled throughout the process during still-water inflation and deflation tests and its behaviour was very repeatable. The behaviour also agreed well with the finite element analysis of this process.

Figure 4: functional testing of the MASIV system; (left) air tightness testing prior to test and (right), measurement and recording of inflated shape in the water

Membrane behaviour when the hull was agitated in the water was also very encouraging. Hull movement approximating 3-5m wave heights were induced thus imitating the effects that wave action will have on the membrane. The membrane was well controlled by either internal pressure or external hydrostatic pressure for the majority of the inflation/deflation process. The generally benign nature of the membrane during these tests indicates that a MASIV system can be designed with the required reliability and lifespan.

Impact drop tests with full-scale impact energies of close to 1MJ were conducted. This is equivalent to the impact of a 500Te multicat style vessel such as the Vow Viking at speeds of 3.8knots. From these tests, it has been concluded that the inflatable volume comfortably meets and exceeds the requirements of the functional specification.

1.4.3.2 Performance Tank Test Conclusions

A tank test model to test the MASIV technology was designed and assembled using ex-Pelamis Wave Power instrumented and motorised joints on loan from Wave Energy Scotland (WES) and Quoceant designed tube sections that enabled two model configurations, namely, High Volume (HV) and Low Volume (LV). This model was tested at the FloWave test facility in Edinburgh in July 2016. The tests conformed to the requirements set out by WES and were independently witnessed and reviewed by third party verifiers, EMEC.

Tests were completed over a range of different significant wave heights and energy periods. This included all WES standardised sea states (long-crested waves and in the highest occurrence region of a typical North Atlantic occurrence table). In addition to these sea states, since one of the major benefits of the LV configuration should be increased survivability in extreme sea states, it was important to test in more extreme seas as well. The crucial wave parameter for a line-absorber style WEC in terms of survivability is the wave steepness. A series of 4 extreme, irregular, long-crested, waves that moved up the steepness limit contour were also tested.

The key findings and conclusions of the performance test programme are as follows:

- Using the same control in both cases, the change of model configuration from high-volume (HV) to low-volume (LV) significantly changed the model response;
    - Compared to the HV model, the power absorber by the LV model is greatly reduced (by factors) as a result of crest-diving.
    - Compared to the HV model, the LV model exhibits significant reductions of maximum angles (a measure of survivability) in extreme seas by around 50% in short period seas, falling to 30% reduction in the steep sea with greater wave periods.
- Comparisons of the experimental and numerical results yielded excellent agreement for the HV model under diagonal or pitch-only MIMO control. The 2d-linear and 2d-non-linear simulation methods are seen to be highly reliable for their use in evaluating annual average power predictions with a mean agreement of 101% and 98% respectively across the seas tested.

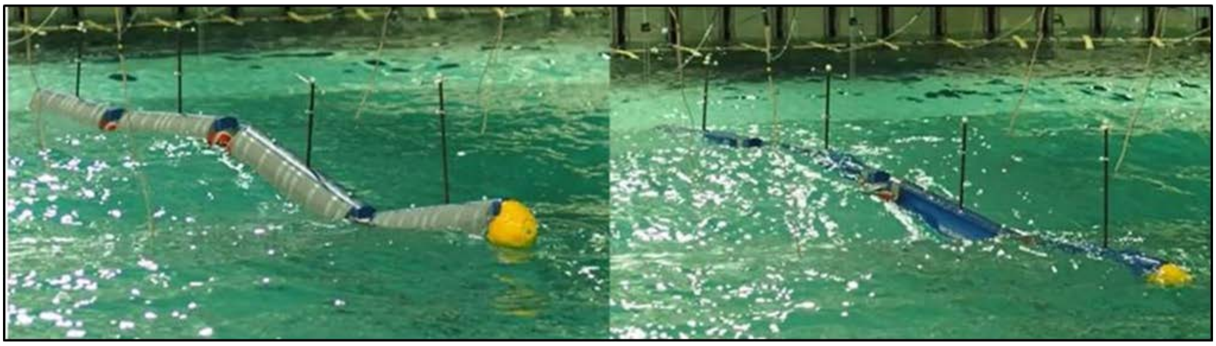

Figure 5: Captures from synchronised video of HV & LV models in WES standardised sea state (IR9, Hs = 4.5m, Te = 9s)

1.5 Summary of Performance against Target Outcome Metrics

A summary of the project target outcomes and updates on each target after completion of the project is included below.

Affordability – LCoE:

The exciting motivation for this innovation was that it has the potential to dramatically reduce LCoE. It has been confirmed that significant and transformative LCoE reductions, achieving the project target of 25-50%, are deliverable. As well as demonstrating a step change in opening LCoE figure, it is also reasonable to assume that this innovation will reduce longer term asymptotes and floor costs. The innovation therefore has the potential to massively reduce the 'cost to commercialise' or 'cost to converge' for a wide range of WEC configurations.

Quantitatively, the high-level conclusion from this work is that the project target of confirming that a 25-50% reduction in LCoE has been achieved. A MASIV line-absorber with a readily achievable PTO damping achieves a 30-40% reduction in LCoE from a non-MASIV benchmark. Larger LCoE reductions of up to 50% can be realised if either the transition point wave height limit can be increased above the current specification or the damping levels of the PTO and WEC can be increased, the former may be demonstrated through stage 2 risk mitigating tests and latter may be eminently achievable in the near term given the increased height of the MASIV hull structure and developments in PTO technology already underway.

LCoE was targeted directly since this is the only real measure that can be used to determine success – the complex and sometimes subtle interaction of all other metrics can be hidden if not. For example, Quoceant initially developed a 3-joint MASIV WEC in the belief that CAPEX reductions from having fewer joints would outweigh yield increases from extra joints. This was not borne out and a 4-joint WEC of the same length and overall volume was shown to have a lower LCoE.

It is possible that further major benefits can also be realised with this system if the underlying WEC parameters are optimised further. This project was focussed on demonstrating positive impact of volume change and not on optimising the underlying WEC concept. However, this study has also shown that there is merit in a much broader search of parameters future work to confirm and assess other configuration changes enabled by the survivability and absorption benefits of the MASIV innovation. It is exciting that this could lead to further major reductions in starting and long term LCoE not captured here.

The MASIV innovation also mitigates against many of the risks associated with operating in more energetic environments and opens up these high incident power site to development. On that basis, LCoE reductions of over 50% may be achievable. For a high incident power Western Isles site, which could potentially now be developed with reduced risk as a result of the MASIV innovation, LCoE figures calculated reduce well beyond the WES target of £150/MWh at 1GW of installed capacity.

Affordability – CAPEX:
The project target was to achieve the LCoE target above, a CAPEX target that MASIV must not increase the CAPEX of a base WEC by more than 10-20% is required. This target has been achieved with the cost of the reference design WEC incorporating the MASIV system actually estimated as cheaper than the benchmark WEC configuration (based on WEC cost metrics and supplier consultation for determination of specific MASIV costs).

Many examples of air filled volumes available with a wide-range of complexity and materials identified. It is anticipated that the MASIV concept could be developed utilizing design details that are already implemented in industry thus minimizing cost. Based on cost metrics from suppliers, it is estimated that the MASIV inflatable structures and associated inflation/deflation systems will account for ~10% of the overall WEC CAPEX.

The main structural fabrication cost increase as a result of the more complex rigid hull shape required to implement MASIV is somewhat controlled due to the structural advantages a taller/thinner hull shape can confer. However, the MASIV enabled WEC also has a major advantage over the base WEC configuration. The survivability benefits of being able to move to the low volume configuration mean that extreme joint angles and joint loads are significantly reduced and are now in line with the angles and load requirements for high power production. This means that more efficient structural designs can be achieved making more efficient use of available angle and moment. As a result, a benchmark, fully survivable, circular WEC configuration would have a higher CAPEX than the MASIV equivalent. Although there is uncertainty in the value, an overall CAPEX reduction of ~5% is estimated.

Yield (Performance):
A target outcome to engineer a system to deliver a 30% to 100% increase in yield was set at the project outset. This target has been achieved. A 36% uplift in power capture has been demonstrated through comparative numerical modelling work (Shetland site). It could also be argued that a MASIV system mitigates many risks associated with deployment in more energetic environments. Therefore, it opens up high incident power sites to development when previously they were ‘out-of-bounds” on the basis of said risk. On that basis, yield improvements of 70% are achieved.

From numerical modelling work the following results were obtained:

- With applicable moment limits for each, the 4-joint MASIV WEC absorbed 36% more power than the benchmark WEC.
- The power capture differences between the two configurations are highest for the high-power Benbecula site. The uplift from inclusion of the MASIV system decreases as the incident power of the site decreases (from 40% uplift for a Western Isles site to a 34% uplift at EMEC)

Yield improvements beyond this can, no doubt, be achieved if further WEC optimisation work is completed.

Survivability:
The target for stage 1 was to demonstrate the improved survivability characteristics through demonstration of extreme angle reduction during tank testing. The target was achieved and 30-50% reduction in maximum joint angles demonstrated across the conditions tested.

Specific design details such as submergence to an optimum level or possibly partial deflation of the MASIV system (applicable only to certain WEC types) may confer additional benefits across a wider range of conditions.

Availability / Reliability / Integrity:
The main target outcome was that a MASIV system can be realised with sufficient reliability to have no significant negative impact on the overall availability of the WEC. In addition, confirmation that the system can be designed to be 'failsafe' to prevent it impacting negatively on survivability was also targeted. Technical assessment of possible MASIV concepts, including details such as fabric characteristics, fabrication complexity, and attachments, has not identified any issues that affect availability if the design process is undertaken with due care and attention. The target of ensuring, with a good confidence level, that a MASIV system can be designed which ensures no significant change in availability has therefore been achieved. An FMEA also confirmed that failsafe system design is also achievable.

The project mitigated many of the potential technical barriers of using a flexible membrane. The many solutions available give good confidence that such a system can be specified and designed. However, Quoceant are also targeting additional qualification testing in stage 2 to confirm this assertion further. System specification and design of the inflation/deflation pneumatic system has also been completed. No technical barriers to system development were identified. This means that, within the inflation and deflation system, there should also be no barriers to delivering a system reliable enough to maintain the availability characteristic of the WEC.

Maintainability:
The target for MASIV is that it should be maintainable & replaceable without a need for specialist, expensive equipment or plant. Technical assessment of the design concepts has not identified any reasons why this target could not be achieved providing it is considered properly during any detailed phase.

The mass of the inflation units should not prohibit the MASIV system being replaced at a quayside with minimal specialist equipment. Additionally, the clamp systems being proposed should enable this process to be conducted in a relatively short time, with minimal personnel and minimal tooling requirements. Internal systems will also be developed in modular fashion to enable FAT testing of complete systems where possible prior to assembly into the WEC. Modular design will also allow simpler replacement of systems.

1.6 Communications and Publicity Activity

Quoceant have actively publicised this project in the following ways:

- WES Annual Conference 3minute elevator pitch
- WES Annual Conference A2 Poster
- ICOE conference stand poster

- Quoceant website news (www.quoceant.com)
- Quoceant website blog - tank testing updates and videos (and shared via LinkedIn and twitter)
  - https://www.quoceant.com/single-post/2016/11/07/Three-year-collaboration-between-EMEC-and-FloWave-offers-wave-and-tidal-energy-developers-%E2%80%98try-before-you-buy%E2%80%99-site-simulation-capability
  - https://www.quoceant.com/single-post/2016/07/21/Quoceants-Inflatable-Hull-Technology-Innovation-Hits-the-Wave-Tank
  - https://www.quoceant.com/single-post/2015/11/02/Quoceant-win-contract-to-develop-novel-inflation-system
  - https://www.quoceant.com/single-post/2016/08/01/EctactiHull-Tank-Testing-Complete
- FloWave/EMEC press release for Ocean Energy Europe: "Ocean energy researchers replicate site-specific ocean conditions better than ever before"

1.7 Recommendations for Further Work

The main technical risks associated with the inflatable membranes relate to robustness and life and, most notably, at the point at which the transition between high volume and low volume is being made. To reduce this risk, further technology qualification and functional testing will play an important part any stage 2 project. To that end, a series of qualification tests should be conducted. Test design will be further informed by additional finite element analysis work and tank testing work that characterises conditions more accurately. It should include seam strength tests as well as preliminary fatigue tests on samples including high risk features such as seams and clamps. Puncture resistance tests may also be necessary; the goal would be to confirm that, in the event of a cut or puncture, the puncture does not propagate beyond the site of damage. This would minimise the impact of puncture and enable reparability, an important feature. Through this suite of individual qualification tests mitigating specific risks, the risk of membrane life not being great enough will itself be mitigated, however, additional separate life-cycle testing may be also required in future. This can be reassessed during a stage 2 project.

The MASIV technology is also not specific to a given machine type or concept. Within a stage 2 programme, it would be prudent to undertake a brief investigation of the applicability of MASIV to other WEC devices to ensure maximum benefit from the development of this innovation. This parallel development work will ensure technology readiness should the opportunity arise to test the system on alternative candidate WEC.