Netbuoy Project

WES Structural Materials and Manufacturing Processes Stage 1 Public Report

Tension Technology International Ltd

This project has been supported by Wave Energy Scotland

1 Project Outputs

1.1 Project Introduction

The TTI NetBuoy project focusses on two strands on the path towards cost competitive wave energy – impermeable fabrics to provide compliant and thus load shedding/peak load resistant buoyant modules and fibre rope 'load nets' to encapsulate the buoyant modules, applying distributed restraint loads and agglomerating the distributed load back to a single or number of structural points to connect to the other parts of the WEC system such as the PTO. The load net is seen as essential in enabling the use of fabric buoyant modules as they cannot easily be restrained otherwise – the restraint must be distributed over the surface of the buoyant module

The WEC technology case study for this project has been a generic ground referenced heaving point absorber. Three scales of Netbuoy were considered at the concept design stage with characteristic swept volumes of $10m^3$, $100m^3$ and $300m^3$. The medium sized Netbuoy100 was ultimately chosen for more detailed engineering and cost assessment This was benchmarked against a steel equivalent buoy to demonstrate the cost benefits and potential impact on LCoE, using the WES costing tool. TTI also consider tow forms of Netbuoy 1) assuming machine room is on the seabed 2) assuming machine room is integrated and forms part of the Netbuoy.

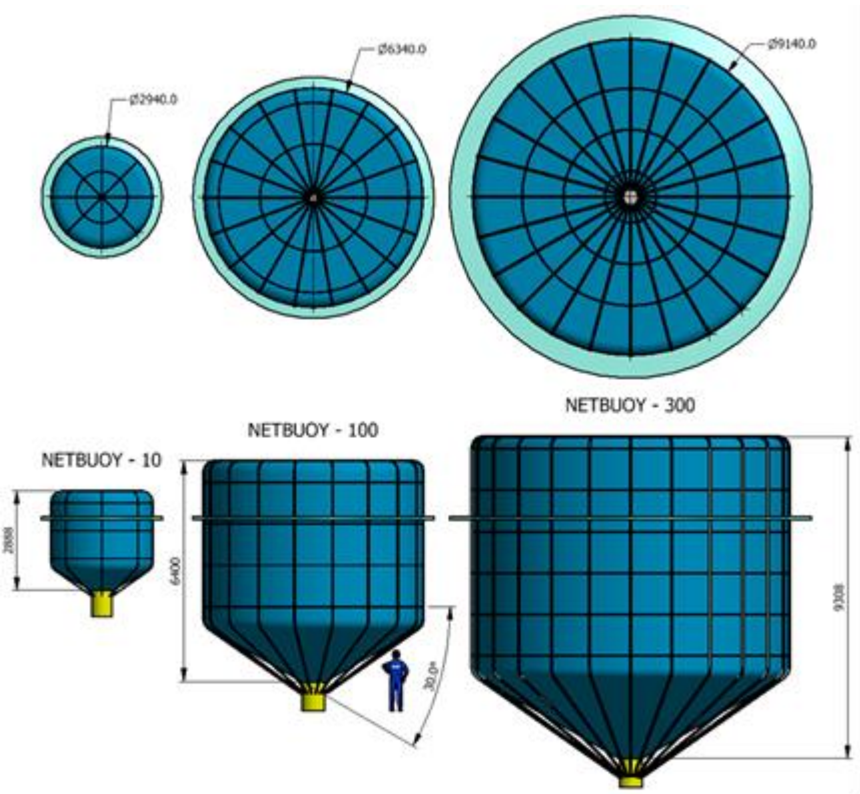

Figure 1: early concept design of three Netbuoy scales (pre FEA modelling)

TTI invited a team of experienced and relevant contractors to participate in Stage 1. The project team is described in Table 1 below:

Tension Technology International (TTI)	TTI was responsible for overall project management and was also responsible for all concept engineering, testing & prototyping, costing assessment and qualification. TTI was also well placed to conduct manufacturing assessment of the Net subsystem based on existing experience. TTI also conducted a detailed Net load sharing assessment of the system using Orcaflex.
TTI Testing (TTI-Test)	TTI testing is subsidiary of TTI and is testing laboratory for mooring lines, components, nets and tension members. TTI testing role was to conduct tests on net connection and assess joint capacity and integrity.
Optimus	Optimus conducted all FEA modelling on the pressurised Netbuoy which was carried out using ABAQUS 2017 software, which is capable of modelling nonlinear materials, contact, fluid cavity ideal gas and dynamics.
Black & Veatch (B&V)	B&V supported on the development of the Basis of Design (BoD) and maintenance of the FMEA and technical risk register. They also collaborated with TTI into the assessment of the technology for other WECs
Quoceant	Quoceant conducted a transport, installability and marine operations study. They completed an cost benefit and availability assessment benchmarking the transport and installation of 10 x Netbuoys compared to 10 x equivalent Steel buoys for an assumed site of manufacture and deployment in Scotland.

Table 1: Stage 1 team

1.2 Description of Project Technology

This combination of elements (Net & Buoy) to provide the prime mover of a WEC means the overall structural mass is significantly reduced when compared to a steel structure by two mechanisms. Firstly the typical density of the materials are around one-seventh that of steel. Secondly, the materials are much more compliant with strain at break typically being achievable between 2% for the stiffest materials (e.g. high modulus Dyneema) to 20% (e.g. nylon) and upwards into hundreds of percent for elastomers and rubbers. This is all compared to steels with elastic limit typically set to 0.2%. This compliance of the inflated structure is inherently 'load-shedding' as the structure is then compliant to peak loads and much less material is required to survive peak loads as steel structures are essentially strain limited (keep deflections at peak load below 0.2% elastic limit) which requires more material to provide the stiffness. Without needing the stiffness to maintain very low strains much less material can be used with synthetic structures. An additional feature of the Netbuoy is that it is readily inflatable and deflatable making it easy and cost effective to transport, deploy and install. A partially deflatable structure also allows for easier at sea connection, allowing pretension of the moorings system via inflation and mitigating the challenge of immersing a steel buoy down under the water for hook up.

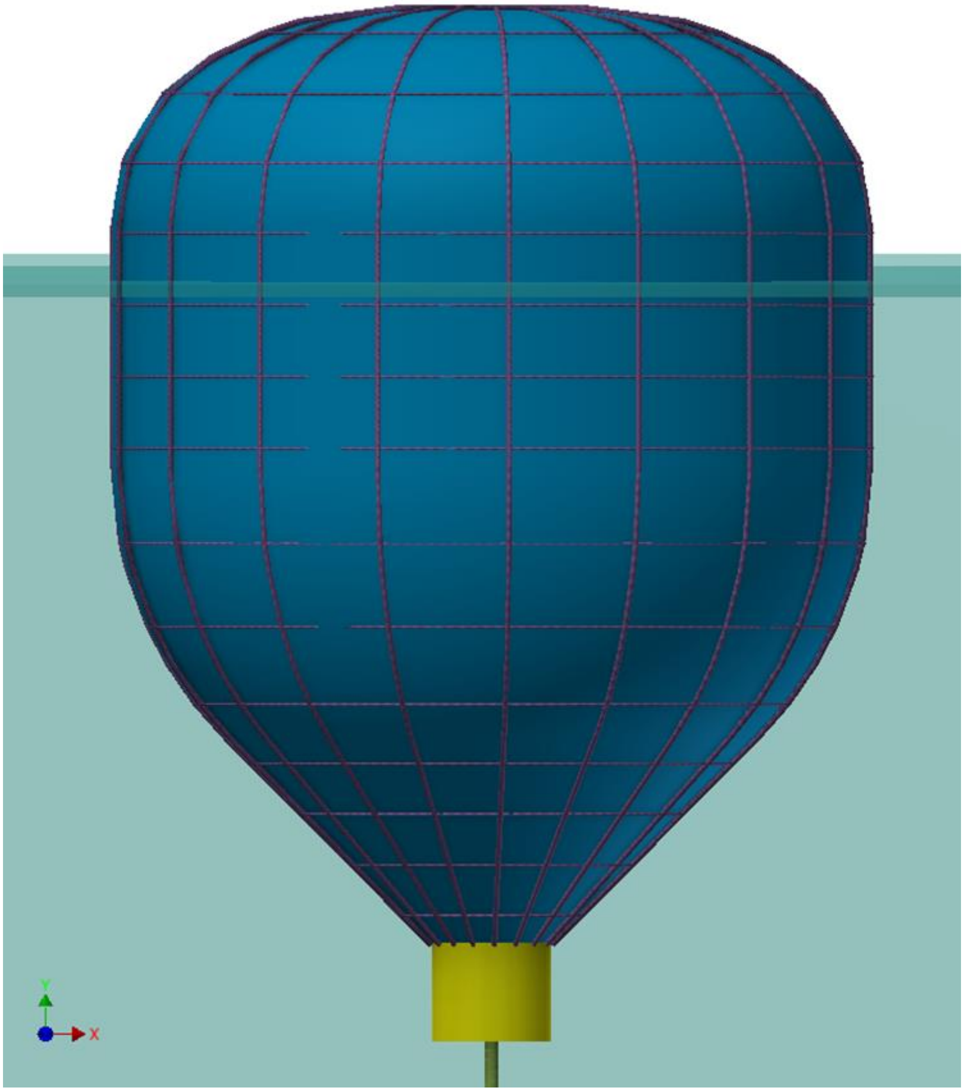

Figure 2: General assembly view following completion of engineering design study work packages – note that the characteristic diameter (diameter at water plane in this case) is the same and the overall height is the same as early concept design

1.3 Scope of Work

The ultimate objective of the Stage 1 project was to show technical and commercial viability of the concept by mitigating the risks through design and demonstrating the step-changes in availability, survivability and affordability and culminating in a relative improvement to LCOE. The work plan and work packages were developed to achieve this. The plan steps were summarised as:

•Develop complete Basis of Design – this defines the technology functions, intended use including environment, expectations and performance metric targets (which have not already been defined)

•Perform technology and threat assessment – assess the novelty of each system/sub-system/component to focus work on key challenges and uncertainties then assess threats, failure modes and risks.

•Develop de-risking plan – develops the plan to design threats out and mitigate them. Many of the key risks were identified at project inception and these has been used to develop the work plan presented herein.

•Execute the development plan – the activities generated by the above steps and as detailed in the work package descriptions are carried out and evidence collected. This is the main expenditure of labour on this project.

•Performance assessment – the evidence collected in the design study and development plan is compared to the requirements laid out in the Basis of Design to assess whether the project and proposed solution are successful. In essence this report is the key vector of overall assessment.

Being a Stage 1 project the majority of the work was to be desk-based and included analytical and numerical studies incorporating the collective's experience in the arena of fibre ropes, elastomers and engineering design in general. That being said two key small-scale tests were planned and carried out: full buoy physical modelling and an element of the restraining net utilising full-scale materials.

A brief description of each of these work packages is included below.

WP1 Project management

Overarching WP covering the entire project duration. The activities included the usual remit of project management including partner communication, data management process and other quality processes, H&S oversight (minor as mostly desk based), WES interfacing activities including attending mandatory WES workshops and contracting.

WP2 Basis of Design

The tasks involved in the development of the BoD included:

- Confirm performance metrics or 'measure of success'
- Propose relevant design criteria
- Define case study WEC which comparisons will be performed on and justify
- Define target site environmental conditions for use in modelling
- Propose relevant/suitable industry standards where they exist (e.g. DNVGL-RP-E305 Design, testing and analysis of offshore fibre ropes)
- Define qualification path for novel technologies based on DNV-RP-A203

WP03 Risk analysis

A systems engineering method similar to that laid out in DNV-RP-A203 (Technology Qualification {for novel technologies not covered by existing validated requirements}) was used to develop the whole work plan for the Stage 1 project. This system engineering approach and methodology gives a structure to the early stage engineering and TRL advancement, whether the ultimate aim is full technology qualification or otherwise.

In simplest terms the threats and risks from the novel technology were assessed and used to generate the work plan to design out, mitigate and prove off these risks. The risk register and FMEA are key tools which are review throughout the development process. As part of this work package the following tasks were carried out:

- Novelty & Risk Assessment / Failure Modes Capture
- Decide on best template to manage risk/qualification: (FMEA/Novelty Assessment template/standard risk template)
- Recommend applicable standards where applicable to less novel issues
- Rank in terms of novelty and prioritise
- Maintain risk register during design phase as new issues arise

WP04 System qualification plan

Leading on from the risk assessment work package described above a full qualification plan was developed to assess the performance to date and form the Stage 2 qualification plan and activities. This plan is directly linked to the key defined and residual risks and the plan is designed to reduce the likelihood or occurrence and impact of the risks. This is a key deliverable to Stage 2 entry and Stage 2 project will pick up on this work and deliver the proposed qualification test plan.

WP05 Material landscaping

The overall objective of Work Package 5 was to examine the materials landscape for both the net and buoyant pod construction meaning a wide-ranging analysis of available and commonly (and uncommonly) utilised polymers and elastomers in analogous systems. The work planned to present the background research conducted and give an overview of a very wide range of materials and then down-select this somewhat to recommendations for material selection for the buoyant pod and net elements. It was planned to do this by:

- Engaging with material supply chain
- Compiling database of impermeable fabrics including properties for buoyant module
- Highlighting key limitations and strengths of the fabrics
- Compiling database of candidate fibre ropes including properties
- Highlighting key limitations and strengths of fibre ropes
- Investigating alternatives for net design (e.g. flat fibre strops)
- Baselining design analogue loads and stresses
- Compiling cost database
- Early consideration of manufacturing challenges for concept designs

WP06 Wave energy capture performance

It was not proposed to develop from scratch a performance description of the candidate WEC. Instead publicly available resources were used to describe the wave power performance on candidate devices against which performance change and relative cost of energy share can be assessed. A relationship between displacement/swept volume and power production was determined based on publically available data and order-of-magnitude first-principles hand calculations and Froude scaling of known performance ‘touch-points’. In this way a performance description for a range of WEC sizes can be determined to compare to the scale family of net and pod designs and be used in LCOE analysis.

WP07 Engineering design study

The engineering design study formed the majority of the technical engineering design study activities in the project. The sub-tasks have been informed by and defined by using the early Technical Risk Register and systems engineering approach. The WP tasks were split into sub-WPs and included:

WP7.1 Concept design

The concept design and concept design report was a key early task to define the ‘family’ of displacements/scales, shapes, net member sizes, buoyant pod constructions and thicknesses and collating early hand-calcs, constraints and so on and created a useful ‘starting point’ for more detailed analyses and input conditions for FEA and suchlike.

WP7.2 Net load sharing

Understanding the load paths though the restraining net structure was identified as a high-criticality activity in the early stages of the project and this sub-task expended significant effort on the analysis of this. It is recognised that a simulation of this system is ideal and it is difficult to assess the impact of imperfections in size/shape/loading. As such the realistic behaviour may be quite different and this will be a residual risk for assessment at Stage 2.

The desired outcome was to understand better the range of net tensions around the buoy in a dynamic wave environment, examine any ‘hot-spots’, consider net safety factors and recommend net member sizes (rope diameters). Net joint design and manufacturability were originally included within this sub-task but were completed and reported in other work package reports as the ‘flow’ of work was more cohesive.

WP7.3 Wear / abrasion

Wear and abrasion of the net-to-buoy interface was also deemed a significant early risk which required assessment and mitigation, which this sub-task was designed to address. Specific detailed activities included:

- Pod-to-net contact pressure assessment using non-linear FEA with appropriately detailed material properties
- Consideration of wear resistant layers on the buoyant pod
- Net coatings considered to minimise rope abrasion
- Designs were investigated to minimise ‘hard’ contact which promotes wear
- The use of low-cost sacrificial or serviceable wear patches on the buoyant pod were investigated and methods for applying these
- Trade-offs between cost and durability were considered with the aim of selecting the best compromise for lowest LCOE

WP7.4 Rigid body proxy

The key change from a conventional steel hulled WEC to the NetBuoy was the fact that the prime mover hull is now a flexible structure. This was flagged as a risk to performance (wave energy capture and conversion performance) as shape changes could denude capture efficiency and volume change is assumed to proportional to capture. As such it was planned to perform shape-change assessment of the buoyant pod would be carried out in non-linear FEA and assess the effect of internal pressure on the rigidity of the hull. The desire was to show evidence that an inflated flexible membrane could fulfil the function of a steel hull in operating wave pressure differentials and thus increase the confidence that the NetBuoy would not significantly denude wave capture performance. It was not proposed to do a full performance assessment as the project team are not WEC developers but materials focussed engineers and a complete candidate WEC was not nominated as the NetBuoy solution should be device agnostic and applicable to many WEC types. As such it was proposed that by increasing confidence that the wave energy capture is not significantly affected to the detriment then the numerator of the LCOE calculation is unaffected and LCOE improvement is wholly affected by the reductions in CAPEX and OPEX which were a key part of other work packages.

WP7.5 Machinery room

It was recognised that the simplest envisaged NetBuoy concept did not provide any machinery room for the prime-path candidate WEC and that the PTO and balance of plant was located subsea outside the buoyant pod. This was much like Seabased, Seatricity and some CETO devices for example and as such was deemed a valid solution path.

However, it was also recognised that this then limits the applicability to other WEC types. The ‘machinery room’ WP was then planned to develop a concept design for a ‘hybrid’ structure whereby the inflated buoyant pod is attached to a rigid steel vessel which contains machinery space and the load net provides secure fixation between the two.

The WP was designed to address the FEED of a machinery room and a concept level assessment of the interface between steel machine room and membrane buoyant pod to assess the risk of wear and effect of pretension in the system.

WP7.6 Buoyant pod impermeability

The TRR raised pressure holding capacity of the buoyant pod to be a key consideration. This WP was designed to address the potential issue knowing that significant pressure losses would be detrimental to LCOE as topping up internal pressure is an energy sink. It was proposed to address this in a manner of ways including comparisons with known products and their standards (e.g. Yokohama fenders), working with previous experience and calculating estimates for acceptable pressure loss rates based on energy consumption. It was noted at the earliest stages of project planning that the buoyant pod impermeability should be the most straightforward of any impermeable membrane based system as it is a wholly enclosed system with no mechanical edge restraint requiring sealing and the shape, volume and pressure were to be largely constant as opposed to continuously varying at wave frequency or otherwise.

WP7.7 Manufacturing process

As with a steel hull the manufacturing cost is a significant percentage of the purchase cost of the hull and this was envisaged to be similar with the buoyant pod and restraint net. As such a work package was dedicated to assess the proposed production methodologies including estimating labour content, net fabrication methods, buoyant pod fabrication methods, opportunities for automation, space requirements, net load joint fabrication to generate a cost-basis for the manufacturing and CAPEX in turn of the NetBuoy system. This was deemed to be a key measure to input into the relative LCOE analysis.

WP7.7 Transport, Installability and Marine Operations

This work package was introduced following project inception to wholly inform the additional benefits of the innovation other than CAPEX. It was decided that an emphasis on all lifecycle phases of the NetBuoy were required to assess this and hence a 'factory-to-site' analysis. The work package objectives were:

- To conceptually develop installation and removal operational procedures for a NetBuoy of 100m^3 volume and comment other scales
- To calculate cost estimates for installation and removal operations for the NetBuoy based on both small and large scale WEC arrays
- To calculate cost estimates for operations of comparative steel based equivalent buoy to enable assessment of cost benefits of NetBuoy
- To calculate cost estimates for load out and transport of NetBuoy and steel-based equivalent from fabrication yard to quayside maintenance base (including road, vessel and ferry transport options)
- To qualitatively investigate and comment on the potential impact of NetBuoy (versus the steel equivalent) on O&M parameters. This will specifically include commentary and potential impact on availability but other key O&M parameters, such as vessel specification, vessel availability and tow parameters for example, may also be relevant and will be considered.

WP08 Small scale system verification

Up to this juncture all work proposed on the NetBuoy system was desk-based. However, the team members have a long history in physical modelling and testing and saw the de-risking and learning value of conducting some small-scale testing and this was proposed as such. Two forms of small-scale test were proposed with the following justification:

- A full buoyant pod model at somewhere around 20th scale (for a c. 5m diameter WEC therefore 0.25 m diameter model) to demonstrate the principle. It was proposed that this would be useful for communication, visualisation and learning about working with scale materials with a view to the future of wave tank testing at Stage 2.
- A single 'element' of the net using full-scale (or near full-scale) materials (I.e one net 'junction' or number of junctions in a grid). It was proposed that TTI group company TTI Testing Ltd would be utilised to simply and cheaply test this junction to show the load transmitting capacity of the proposed joint including full-orthogonal pull at the junction.

WP09 Applicability to other WEC types

The work set out thus far focussed on the most obvious application of the proposed solution – a heaving point absorber (either with or without rigid hull) which is either surface piercing or wholly submerged. The applicability to other WECs WP set out to examine all other key WEC types and propose high-level concept designs for the application of this solution to demonstrate genuine step changing enabling technology. For WECs types where they was no obvious applicability this was to be described and justified.

WP10 Performance assessment against target metrics

The over-arching criteria for success for an alternative material WEC is whether or not it can fulfil the requirements of a WEC hull with lower life-cycle cost. The objective of this work package was to initially define the suite of target metrics and ultimately compared performance with the target metrics. It was proposed initially that this will be compared with a geometrically identical steel hulled prime mover to show the cost benefit in terms of CAPEX, OPEX and installation costs. As stated above it was propose to do minimal work on defining the performance baseline but provide sufficient justification that the performance would be unaffected by the move to a more flexible hull-form. In essence then, this report forms a large part of the performance assessment work coupled with the detailed cost report (Reference 21). The next section of this report describes the target metrics developed in the early stages of the project as these do form the basis for comparison of function and performance.

1.4 Project Achievements

Overall the project has achieved what was intended at the start of the project. This was largely aided by following a structured system engineering approach. Being an R&D exercise, this is always a somewhat complicated exercise but it has largely been shown that the project addressed all work packages and aspects therein. The project work packages have been defined in a risk-analysis type approach with activities and tasks designed to address the key risks and mitigate them. Target metrics were also set out at the project inception although it was known then, and now, that some of the key requirements for a WEC prime mover are difficult to define in terms of a specific measurable quantity but more often a pass/fail against certain criteria or functions is more appropriate.

It has been shown that the project addressed the vast majority of the intended work scope and generated encouraging outcomes through this. Very few aspects of the laid-out work scope have not been 'hit' and this has been justified if so and the open actions carried forward to a future project.

It has been shown that the confidence in the proposed innovation has increased throughout the project, both technically and commercially. The stage 1 cost assessment carried out showed that the NetBuoy prime mover based WEC could reasonably see a 33% to 50% improvement on LCOE compared to an all-steel equivalent, depending on final configuration and location of machine room. Considering the prime move in isolation the Netbuoy is between a quarter to half the cost of the steel equivalent depending on configuration. It is expected that the cost benefit will be further enhanced for the largest scale Netbuoy. These estimates are encouraging and avenues for further work to increase this benefit have been identified. The key technical risks have all been addressed within the context of a Stage 1 project that is largely desk based although the physical testing and modelling carried out was found to be very useful.

The residual technical and cost risks have been compiled and re-ran through the qualification planning progress to generate a work plan for a potential Stage 2 project and they key recommendations for further work are presented below.

1.5 Applicability to WEC Device Types

TTI along with B&V conducted a review of the applicability of the Netbuoy to othe WEC devices. Applicability to other WEC types was a key activity in the Stage 1 project. This section summarises the outcomes of that work package. In general terms it was concluded that any device requiring water plane area or displacement for energy conversion may benefit from the application of a NetBuoy type system. The overall objective was to assess whether a NetBuoy system could replace large hulls in either steel or concrete.

Device Family	Applicability	Justification
Attenuator	Yes	The applicability to attenuators was deemed as being good. Assessing the field of attenuators suggested two subsets – long spine devices with constant cross-section and water plane along the spring and hinged rafts with concentrated water plane at the extremities of lever arms. For the spine device a rigid steel spine with mechanical hinges was envisaged with the additional required buoyancy being provided by slender NetBuoy systems being 'strapped on' to the spine. For the hinged rafts a similar manifestation was envisaged but with more round or lozenge shaped buoyancy pods being located at the extremities, again attached to the rigid load frame with a restraining net.
Point Absorber	Yes	The applicability to point absorber (PA) devices was deemed to be very good and the PA concept was the prime-path device throughout the Stage 1 project. The prime path PA concept has two variants whereby the buoyant volume is almost wholly replaced and partly replaced at some significant percentage. The remaining rigid structure is dubbed the machine room as it may house the PTO and ancillary equipment whilst providing the single-point or multi-point connection to the mooring system. This manifestation was based around a vertical 'splitting' of the hull whereby the 'top' was replaced by a single NetBuoy assembly and the overall aspect ratio (AR) (height over diameter) might be around unity. For larger devices where AR is desired significantly less than unity, or ones which required a central rigid machine room, a concept was developed whereby a series of buoyant pods could be arranged around the periphery of the PA forming an approximation of a toroidal ring. This was seen as a good modular approach to scaling up with numerous advantages such as increased overall diameter (if desired), redundancy/ALS, protected central machine room and suchlike.

Device Family	Applicability	Justification
Oscillating Wave Surge Converter	Yes	The applicability to OWSC was deemed to be good. A concept design was developed whereby the conventional flap-type structure could be replaced by a ‘ladder-frame’ type structure in steel (or otherwise) which houses long cylindrical NetBuoy assemblies with the net restraining the buoyant pods to the rigid frame. Numerous advantages were envisaged including lighter transport weight, easier installation, modularity for maintenance and repair, redundancy and structural compliance and fatigue life in extreme seastates.
Oscillating Water Column (OWC)	No	Some relevance to OWC devices was noted with NetBuoy but only for floating devices where wholly rigid hulled buoyancy tanks, if they are utilised, could be replaced by NetBuoy assemblies. Obviously zero applicability to shore-based OWC.
Overtopping/ Terminator	Yes	The argument for overtopping applicability is similar to OWC but with a further, perhaps more radical, concept of application. It is offered that long, slender NetBuoys could be arranged to provide the collector arms of an overtopping device and these could be cable-stayed back to a rigid central hull. This would overcome challenging steel construction to accept the induced bending stresses in the long arms and provide compliance such that overall bending moment is reduced. The application may look very similar to analogous designs such as marine booms or inflatable dams.
Submerged Pressure Differential	Yes	For the form of SPD device which is similar to a point absorber then the PA arguments are applied here also and good applicability is seen. Additional challenge would need to be overcome to sustain the increased hydrostatic head but this is seen as quite realistic. For the alternative class of SPD such as membrane based volume change devices less applicability is envisaged.
Bulge Wave	No	Much like OWC devices minimal applicability is noted unless substantial rigid volumes are used on bulge wave devices for additional localised buoyancy, which may be the case. In this instance NetBuoy would seem ideally matched as there are then material synergies between bulge wave tube and additional buoyancy and the overall system would seem well-matched.
Rotating Mass	Yes	Again, where water plane area (WPA) and displacement/buoyancy are required we see application for the NetBuoy system. The application to a rotating mass device is perhaps not immediately obvious without understanding more about the hull shape and required WPA but we do see some

Device Family	Applicability	Justification
		scope for application.
Other	Yes	As with the majority of device types already assessed if a different kind of device requires water plane area and displacement/buoyancy then we see potential to integrate NetBuoy systems to provide this at lower cost than a steel hulled equivalent. We also see good possibilities with integrating with certain type of floating tidal energy convertor which is encouraging in terms of making the overall system economically attractive.

Table 2: Applicability to other WECs

1.6 Communications and Publicity Activity

The team at TTI has published a significant number of papers in the past (any future papers will be referenced at www.tensiontech.com/papers) and this is something we will consider doing for the future for Netbuoy now Stage 1 has been completed. To date public dissemination has been minimal until we have finished Stage 1. We would look to build on this.

1.7 Recommendations for Further Work

The TTI Qualification plan which was developed in accordance with DNV-RP-A203 is the controlling document for the definition of a Stage 2 work plan. Identical to the generation of this Stage 1 work plan the DNV approach to qualification of new technologies has been adopted and the input conditions are the outputs from the Stage 1 project.

The Stage 2 project requires much more physical testing commensurate with the Technology Readiness Level. In terms of design and analysis work the key work packages within Stage 1 shall be extended and improved upon to capture the Stage 1 learning and develop a more thorough understanding of the system. To this end the main design and analysis recommendations for further work are:

- Detailed Orcaflex analysis of net load paths, load sharing, more detailed description of environment, assess installation condition.
- Detailed non-linear FEA assessment of buoyant pod construction and local interactions with the restraint net
- Mechanical engineering design of ancillary systems such as rigid node and air inflation valves.

The key experimental work packages are:

- Full-system design and build at appreciable scale. This includes net termination interface to rigid node or machine room
- Inflation and air holding tests

- Submergence test and dynamic wave testing at appreciable scale
- Net-on-buoy abrasion testing
- Net junction capacity testing
- Puncture resistance (low priority)

Our qualification plan which was completed under Stage1 gives much more detail on the proposed lay-out for these testing work packages including concept designs for the test rig arrangements. Further work is also recommended on developing a road map to commercialisation and associated manufacturing studies. More closer supply-chain and manufacturer engagement is planned for the stage 2. The LCoE model will be developed further based on the outputs of Stage2.

1.8 Useful References and Additional Data

1. TTI-TM2017-2291-R1009-Rev00 FINAL TECHNICAL REPORT. NetBuoy Stage 1 – final report to WES with all key references (**Confidential**)
2. www.tensiontech.com (website will be used to promote Netbuoy in the future)