NetBuoy Project

Structural Materials and Manufacturing Processes

Stage 2 Public Report

Tension Technology International Ltd

This project (NetBuoy II) has been supported by Wave Energy Scotland

1 Project Outputs

1.1 Project Introduction

The Stage 2 project was the natural follow-on from the Stage I project with all activities proposed and conducted in Stage 2 formed by the residual technical risks and the ensuing qualification plan formed at the end of the Stage I project. The overall aim of the Stage 2 project was to progress the system to moderate TRLs (Technology Readiness Levels) and complete FEED (Front-end Engineering Design) engineering, supported by qualification tests and engineering & manufacturing studies (Refer to Figure 1).

The Stage 2 NetBuoy project encompassed two areas Tension Technology International Ltd (TTI) sees as being key to 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.

This combination of elements to provide the prime mover of a WEC (Wave Energy Collector) means the overall structural mass is significantly reduced when compared to a steel structure by two mechanisms. Firstly, the typical density of the materials is 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 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. The inflatable nature of the prime mover also affords significant advantages at the manufacturing, transportation and installation phases.

The WEC technology case study for this project has been a generic ground referenced heaving point absorber (section 1.7 of this report details the high applicability to other WEC architectures). 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 (Levelised Cost of Energy), using the WES costing tool. TTI also consider two forms of NetBuoy: 1) assuming machine room is on the seabed; 2) assuming machine room is integrated and forms part of the NetBuoy (as detailed in Figure 2 & 3.

This report provides:

- Description of project technology
- Overview of scope of work and project achievements
- Recommendations for further work

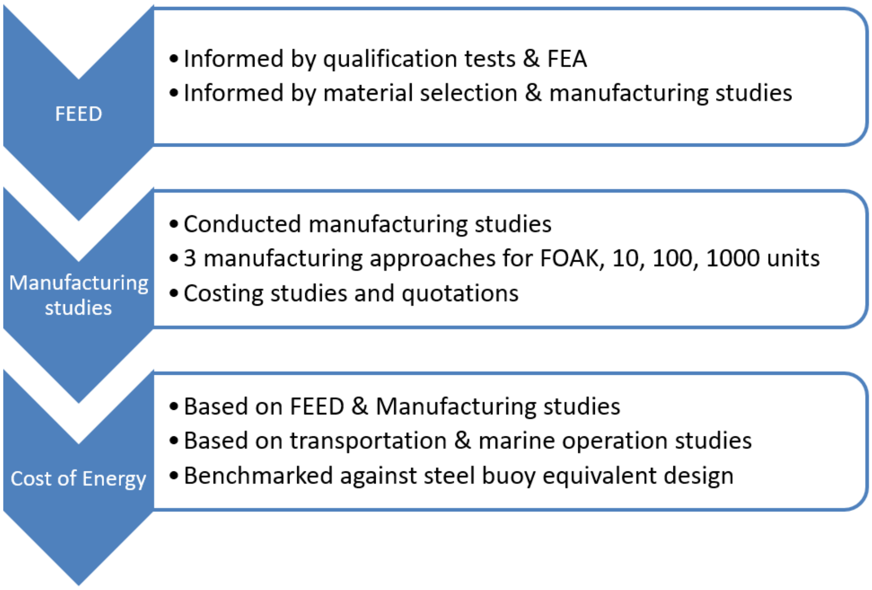

Figure 1: Stage 2 process chart

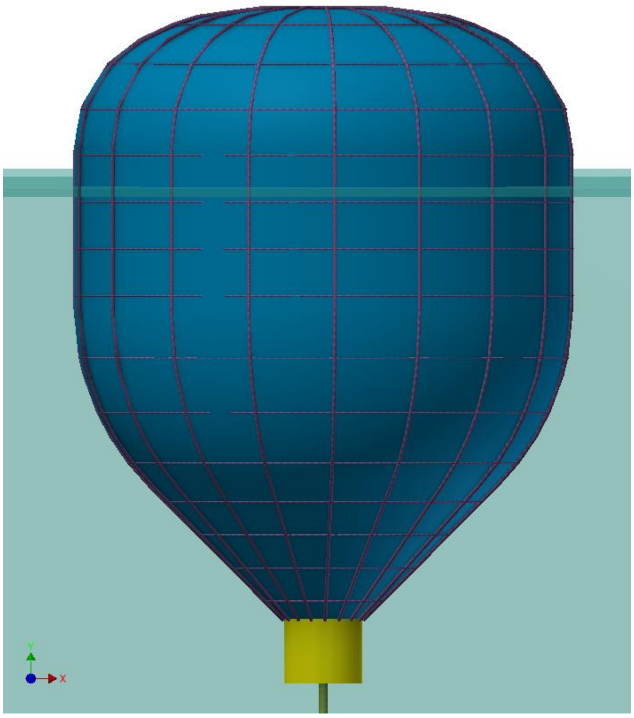

Figure 2: NetBuoy without machine room

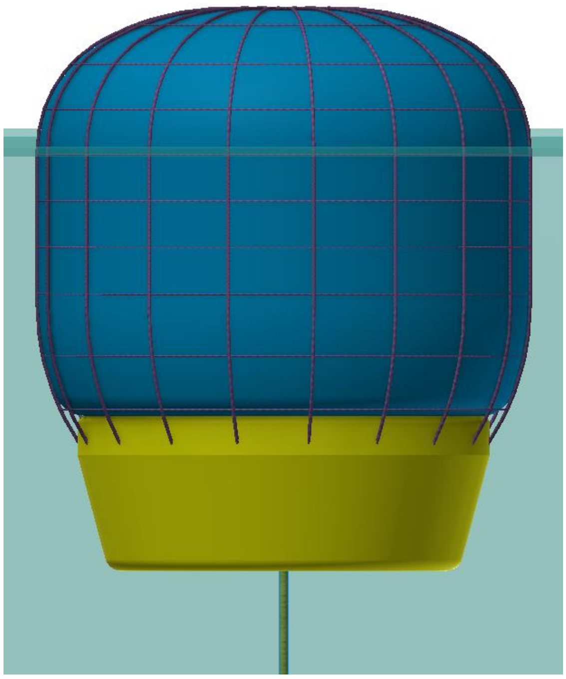

Figure 3: NetBuoy with integrated machine room

TTI invited a team of experienced and relevant contractors to participate in Stage 2 (Table 1), several of which participated in Stage 1.

Table 1:NetBuoy Stage 2 Project Team.

TTI	TTI was responsible for overall project management and technology development and was also responsible for overall FEED, system and subsystem testing, costing assessment and qualification. TTI was also well placed to conduct manufacturing assessment of the Net subsystem based on existing experience.
GRIFFON HOVERWORK	Griffon Hoverwork Ltd are specialists in technical development of hovercraft and skirt systems and have applied their know-how in the design and manufacture of membrane systems for other marine applications and several wave power projects. In the Stage 2 NetBuoy project they designed and manufactured scale NetBuoy pods for tank testing and the test pillows for abrasion testing. They also conducted manufacturing and costing studies for commercial scale production options and conducted FEED design for the full-scale buoyant pod.
TUN ABDUL RAZAK RESEARCH CENTRE MALAYSIAN RUBBER BOARD MRB	TARRC (Tun Abdul Razak Research Centre) – Malaysian Research Board. TARRC were engaged by TTI to provide specialist advice into materials selection, environmental degradation and aspects of manufacturing. TARRC also reviewed manufacturing studies conducted by Griffon Hoverwork and participated in associated workshops.
Optimus Engineering with Character	Optimus is an independent engineering consultancy with offices in Aberdeen and Inverness. It has a large Structures team including engineers and designers and has an Advanced Analysis capability using non-linear Finite Element Analysis tools. Optimus conducted all FEA modelling on the pressurised NetBuoy carried out using ABAQUS 2017 software, which is capable of modelling nonlinear materials, contact, fluid cavity ideal gas and dynamics.
University of Strathclyde	The Kelvin Hydrodynamics laboratory (KHL) is part of the Department of Naval Architecture, Ocean and Marine Engineering (NAOME) at the University of Strathclyde. The lab houses a wave/towing tank of dimensions 76m x 4.6m x 2m (typical water depth). NAOME researchers have many years of experience in evaluation and analysis of performance of fixed and floating structures including a wide range of wave energy devices both in research projects and industry studies. Hydrostatic and dynamic tank testing of the NetBuoy system were conducted at KHL.
Quoceant Innovation Offshore	Quoceant are an independent engineering and design consultancy based in Edinburgh, with specialist expertise in the wave sector. Quoceant conducted transport, installation, marine operations and O&M studies. They completed a 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.

1.2 Description of Project Technology

The NetBuoy is a system level materials innovation coupling two technology and materials strands TTI see as being pivotal in the path towards cost competitive wave energy extraction; impermeable membrane buoyancy pods and fibre rope encapsulation nets. Recognising that many/most WECs utilise large volume hulls to achieve the displacement and swept volume required for wave energy capture the inflatable membrane buoyant pod is seen as a highly effective way of replacing heavy and expensive steel hulled structures. The membrane buoyant pod is a simple engineered system comprising elastomer impermeable layers (which are abrasion and UV resistant externally) and polymer cord reinforcement layers which allow increased membrane stresses and modest strains. When inflated to modest operating pressure (e.g. 80 kPa for 6m diameter pod) the pod is exceedingly rigid with measured diameter changes over a range of external pressure loads of around 0.2% of diameter. In this manner its wave energy capture performance behaves as if it were a rigid steel structure. The pretension induced in the membrane due to the internal pressure results in a mean strain in the order of 2% which is compared to a breaking strain in the order of 12-15%. This shows a large factor of safety on ultimate load. Tank testing in the Stage 2 project demonstrated that there exists no mechanism to induce large increases in internal pressure; the internal pressure varies only modestly with external waves, so the dynamic strain range is small. To this end then with low mean tension and low dynamic tension in the membrane, fatigue calculations have shown that the fatigue life of the buoyant pod is well in excess of the typical 20 to 25-year project life span. Indeed, fatigue life of hundreds of years is expected showing a large design fatigue factor. Further, despite being globally rigid and with low overall strain range under severe wave impacts the system is of course still flexible. The membrane has very low bending stiffness and extreme wave events can harmlessly and temporarily deflect the membrane surface with no lasting damage. A similar event on a ribbed steel structure could, and often does, result in permanent deformation as the steel 0.2% strain limit is exceeded even with thick (and hence heavy and expensive) shells being specified for this reason. This highlights the structural inefficiency of steel hulls for WEC applications as the hull mass is driven by rare extreme events and the cost is high because of this. Further important benefits of the inflated pod, over equivalent rigid structures include the ease to transport and install.

The uninflated form can easily be packed and transported in standard containers whilst the equivalent rigid structure would need towed to site. Containerised transport opens supply-chain options globally which is cheaper. Installation is also facilitated via partial inflation of the buoy at point of hook-up. The light weight is also a benefit to transport and installation.

Although environmental protection is required (UV and ozone) no corrosion protection or repair of corrosion protection is required. UV and ozone resistance are dealt with by appropriate elastomer selection.

The key system level engineering challenge with a membrane buoyant unit is the attachment to the remainder of the WEC system. This is largely straightforward with a rigid hull as the stiff nature of the material lends itself to point-load attachments for moorings and PTOs, for example. Addressing this challenge with the buoyant pod required the innovation to be a system and this led to the development of the restraining net. The net envelopes the buoyant pod with numerous strength members to distribute the restraint force over a large area and agglomerate it back to a number of ‘hard-points’ to tie into the remainder of the WEC structure. The strength members of the net are polymer fibre ropes which are well known in the marine industry, and others.

The manufacturing process for the buoyant pod is almost identical to that of ship-to-ship (STS) pneumatic fenders (or Ship-to-Quay [STQ] fenders). These large fenders are incrementally laid-up into a steel mould with tire-cord and are then vulcanised to create a homogenous impermeable membrane. Other manufacturing process options were investigated in detail in the Stage 2 project and options do exist for variants such as forming over an inflated mould (as opposed to inside a rigid mould) and then performing hot consolidation or vulcanisation and this kind of process is utilised for marine air bags and STS fenders that are not certified to ISO17357-1.

The manufacturing process for the restraint net is essentially an assembly process of off-the-shelf fibre ropes. The net assembly can be carried out almost anywhere that space and semi-skilled labour is available. The finished nets are easily and compactly containerised for transport to the final assembly (with pod) facility or location.

In summary, the innovation pursued with the NetBuoy is the system integration of flexible membrane pods (which are fairly known) and fibre rope nets (which are also fairly well known) into a cohesive system for the provision of buoyancy, water plane area and displacement for WECs. Within the overall system numerous "small" innovations are also utilised such as the net connectors, manufacturing methods, shape definition and so on. As detailed in section 1.5 of this report the technology has high applicability to other WEC architectures.

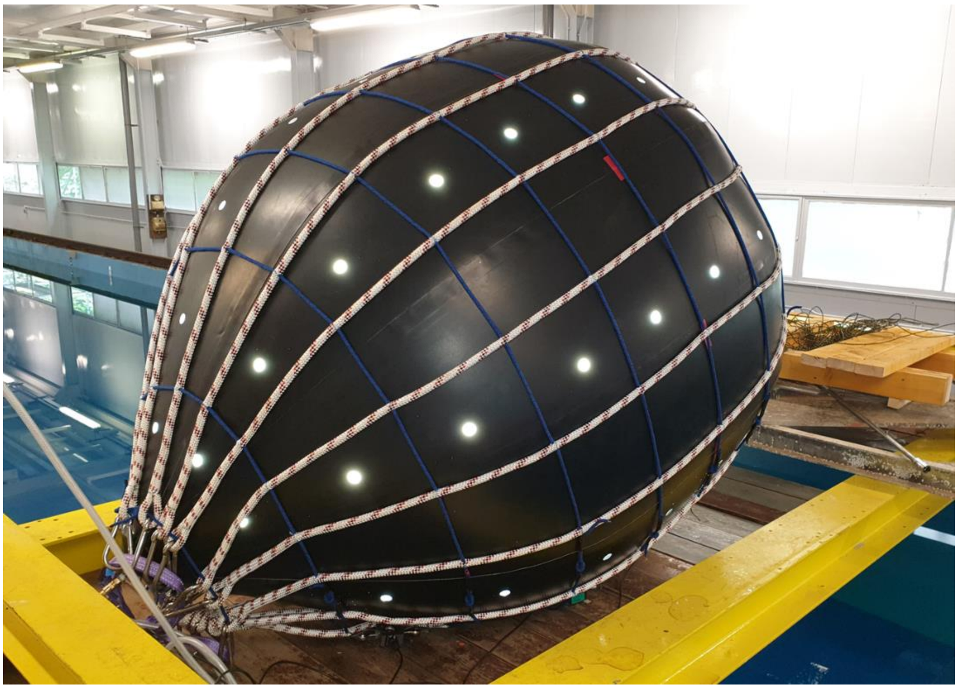

Figure 4: ¼ scale of NetBuoy100 ready for tank testing at KHL

1.3 Scope of Work

The Stage 2 project was the natural follow-on from the Stage I project with all activities proposed and conducted in Stage 2 formed by the residual technical risks and the ensuing qualification plan formed at the end of the Stage I project. The overall aim of the Stage 2 project was to progress the system to moderate TRLs and complete FEED engineering. Mitigating the residual risks from the Stage I project was a significant aspect of this. In addition, the commercial case was to be updated, refined and Commercial Readiness Level increased. The overall objective was to ensure sufficient confidence was accumulated to allow Stage Gate completion and advancement to the Stage 3 project. The key high-level residual risks that the Stage 2 project was designed to mitigate included:

- Buoyant pod shape and shape change with varying external pressures (rigid body proxy)
- Net load sharing
- Net-on-pod abrasion
- Net junction load resistance
- Manufacturing and impermeability of finished pod

The engineering and testing qualification plans were designed to address and de-risk these and advance the TRL and confidence in the system and materials. The key work packages to address these items were:

- Front-End Engineering Design of full-scale system including tooling, ancillaries and manufacturing process of pod. This FEED work package was also used to "pull together" all the other strands of information and learning accumulated in the other work packages to give an overall view and design for the full-scale system.
- Net load sharing - using Orcaflex simulation tool.
- Non-linear finite element analysis of the combined net and pod to assess rigidity of the system under varying external pressure heads and assessing the deformed shapes.
- Full system manufacturing and in-air pressure holding trials.
- Static wet testing at 1/4 scale and dynamic (in waves) testing at 15th scale.
- Net-on-pod abrasion testing for range of material samples.
- Net junction capacity testing for a range of net connection options.

In parallel to qualification tests and system analysis a number of manufacturing studies were conducted for small to large production runs for a commercial scale device. Three manufacturing options were considered, and the output of these studies was also used to inform cost of energy of the NetBuoy system, when benchmarked against an all-steel equivalent buoy.

Examples of qualification tests and complimentary systems modelling are shown in Figures 5 to 18. Project achievements are summarised in section 1.4.

	
Figure 5: ¼ scale manufacturing	**Figure 6: ¼ scale air holding**

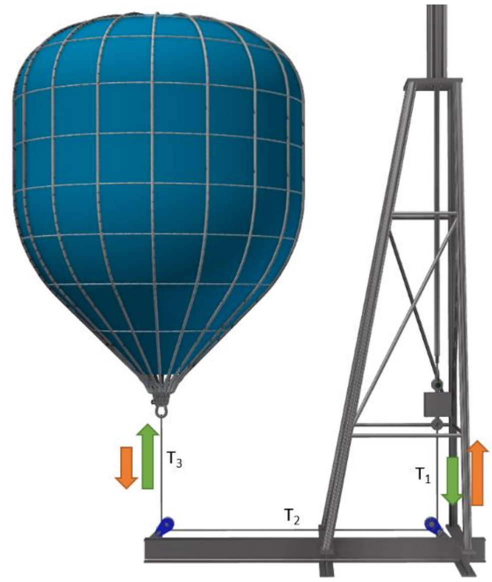

Figure 7: ¼ scale test rig

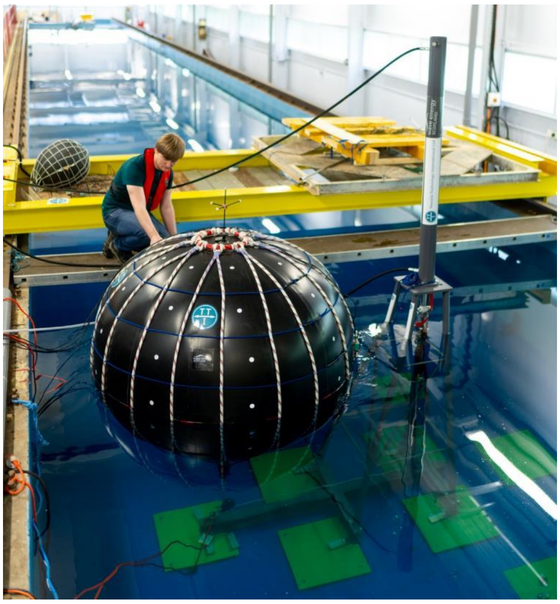

Figure 8: ¼ scale hydrostatic test

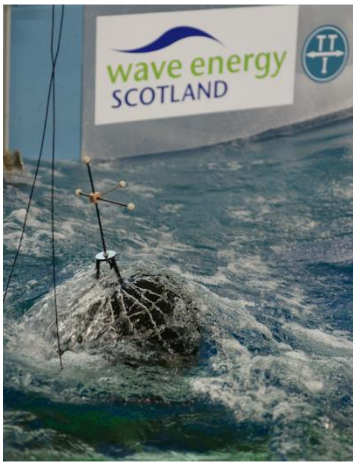

Figure 9: 15th scale dynamic tests

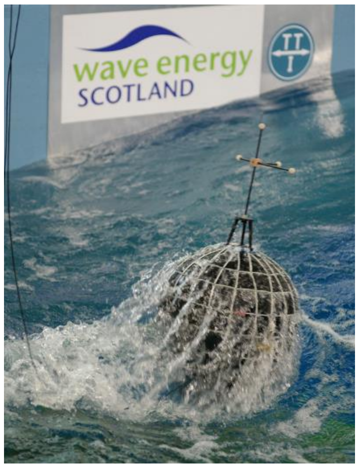

Figure 10: 15th scale dynamic test

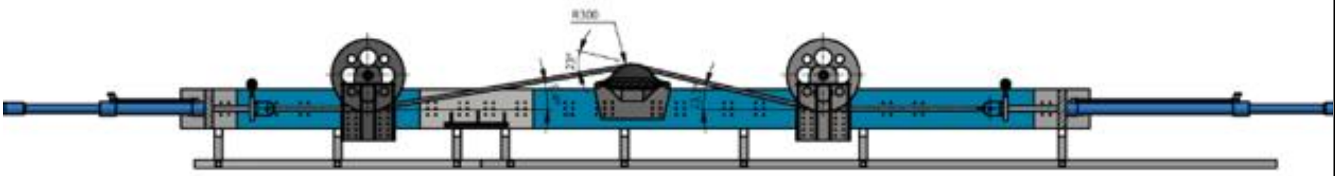

Figure 11: Test rig for full-scale rope on inflated pillow abrasion tests (5 material samples tested)

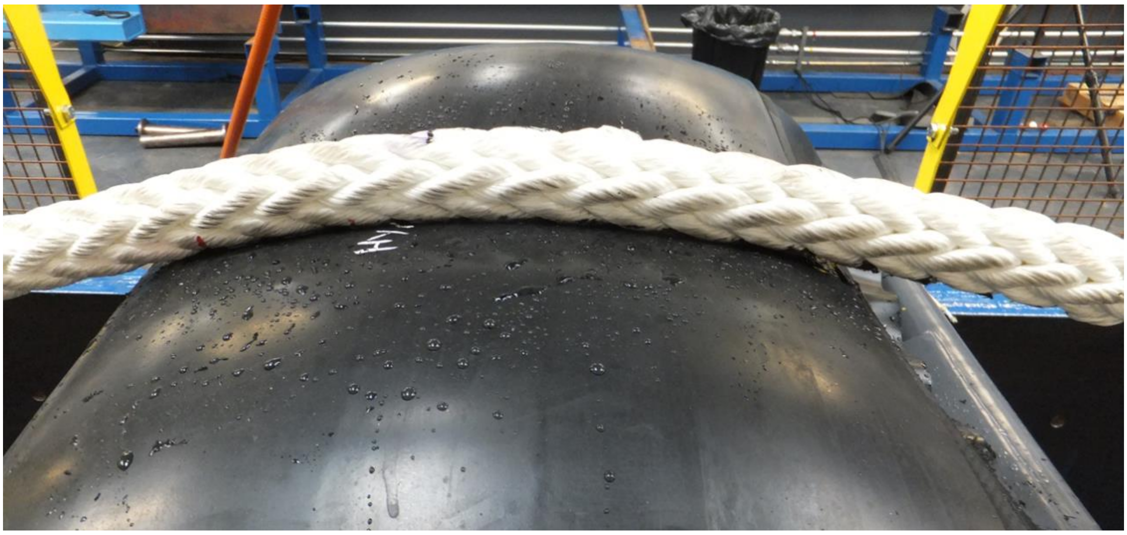

Figure 12: Example of inflated pillow and full-scale rope used in in material trials

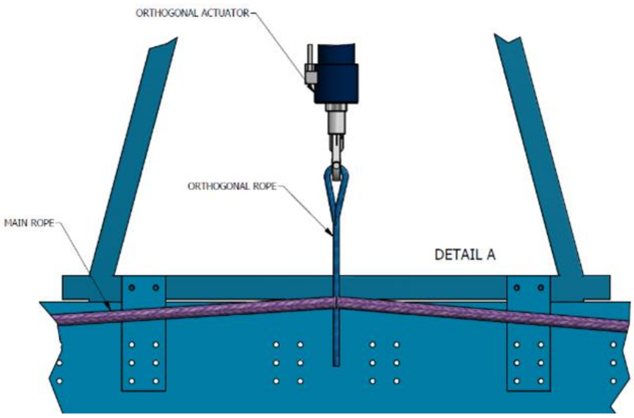

Figure 13: Test rig for rope net junction tests

Figure 14: Rope net junction tests

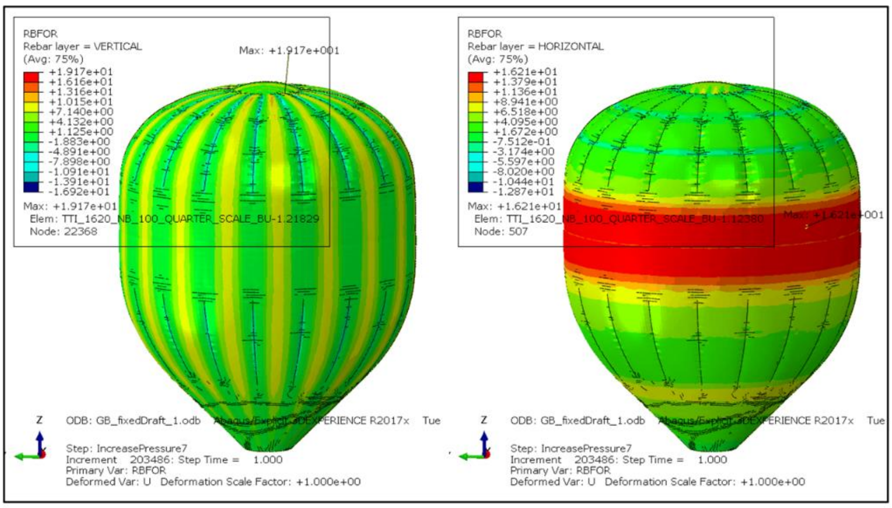

Figure 15: Non-linear FEA stress distribution 3D shape correlated with tank test

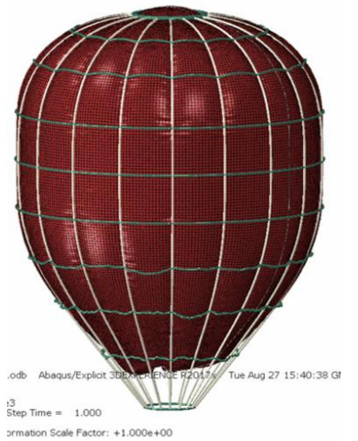

Figure 16: FEA partial inflation trials

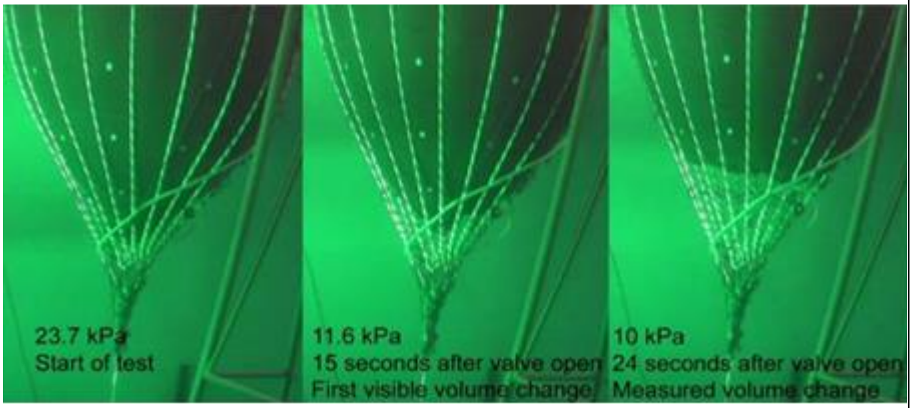

Figure 17: Partial inflation trials correlated with tank tests

Figure 18: Orcaflex modelling

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. All planned qualification tests were successfully completed. Target metrics were also set out at the project inception.

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 any open actions and residual technical and commercial risks will be carried forward to our proposed Stage 3 project.

1.4.1 FEED & Qualification Tests

The manufacture of the quarter-scale system was an extremely useful process. As with any scale model certain limitations exist and it was not possible to make a fully vulcanised buoyant pod (due to tooling cost for a one-off) and nor was it necessary as cold-bonded off-the-shelf membranes were more than adequate and scaled the membrane elasticity well. TTI contracted Griffon Hoverwork Ltd to manufacture the pod which was 1.6m in diameter with total enclosed volume of around 2.7 m^3. The pod was made from 12 gores (panels) of fabric that were cut to shape according to TTI's developed patterns and the finished article matched the desired design shape extremely well. The wet testing showed that the displaced volume at nominal draught was within 0.5% of the design volume. Prior to the wet testing a suite of dry testing was carried out to assess the air holding characteristics of the pod, trial assembly into the net, effect of ambient conditions and so on. It was found that the air leak rate was less than 1% of volume per day and this is without an impermeable liner or homogenised vulcanised construction: full-scale pods, similar in construction to vulcanized marine fenders, are expected to easily outperform this good result. The shipping and assembly of the system gave a profound demonstration of one of the key USPs of the system. The pod arrived in a small cardboard box and was quickly assembled into the net. Following a few minutes of inflation, a buoy with nominal 2 tonnes displacement that weighed only a few kilograms existed. It had been easily carried into the building by one person. No other form of buoyancy (steel, concrete, HPDE etc) could possibly fulfil this function.

Once in the tank the quarter-scale buoy underwent a series of quasi-static tests to ascertain shape change with response to varying internal and external pressures. The results of this testing clearly showed that above an internal pressure that overcame the hydrostatic pressure at the maximum submergence the body acted as a rigid body with indiscernible volume change with respect to external pressure head variances. Motion tracking markers on the membrane were used to measure shape change throughout these tests and the water plane diameter was found to vary less than 0.5% over a very broad range of pressure differentials. The fifteenth scale tests addressed similar aspects but with a dynamic wave field applied. The internal pressure was found to vary modestly with external waves which when correlated with the quarter scale results confirmed that almost zero dynamic shape change occurs on a global level. Meridional line tensions were measured in both models and although somewhat uncertain did give an understanding of the variation along the length of one meridional due to friction against the pod and also the day-to-day variability due to changing set-ups. This led to the development of a stochastic analysis to understand the likely variability better.

The rope-on-pod abrasion testing was a key derisking activity identified in the qualification plan. The detail design of the testing progressed throughout the early phases of the Stage 2 project and eventually made use of inflatable pod sample sections (pillows) to best represent the contact condition between the rope and pod. Five different elastomer samples were bonded to the pillows and a full-scale tensioned rope cycled back and forth over the elastomer. Due to the enforced sliding distance this was a highly accelerated test in terms of total slippage. The selected rope turning diameter (surface curvature) enforced by the inflated pillow shape and the rope tension resulted in an average (over the rope diameter/width) contact pressure very close to that expected in the full-scale system. The pillows did make the test setup more challenging as they underwent global shearing motions prior to the rope sliding on every cycle. However, care was taken to ensure that the sliding distance was as comparable as possible for every sample tested. The measurement of the wear volume on the elastomer showed that some elastomers were excellent in abrasion performance and some were very poor. The rope was largely untroubled by the sliding.

The net junction testing was the last physical testing undertaken and this was a continuation of work carried out in Stage I project whereby a full-scale net "element" (one cruciform net junction) was tested. The meridional (main) rope was held horizontally under tension and the circumferential rope pulled vertically through the joint. Following the tank testing it was found that the most important case for joint "locking" is when the system is not pre-tensioned. Without pretension the plain net joint can easily slip, which is desirable for manufacturing and initial assembly, but it is preferable to have it locked during deployment to prevent the net geometry changing. Once the meridional lines are under tension, they have a "self-locking" function on the net joint due to inter-strand friction in the rope, much like a conventional eye splice (eye splices achieve sufficient internal locking to achieve full rope break load capacity). Numerous methods were trialled before arriving at a viable solution which was further developed and tested. The chosen solution can quickly, easily and cheaply impart joint reinforcement in the un-tensioned condition and also bolster the tensioned capacity.

The manufacturing and FEED activities pulled together all the strands of information and learning from the preceding analytical and physical qualification activities. In addition, a detailed study on three different methods of pod manufacture was carried out. A key learning point from this is that the most attractive long-term volume production method (vulcanised) is not suitable for prototype testing as the tooling cost is prohibitive for a one-off. A hybrid manufacturing approach was also assessed in detail that does not require a metal mould and this is attractive for low-volume manufacture although further process de-risking would be required, and this is identified. In addition to the pod manufacturing the FEED work detailed ancillary components required and also carried out detailed fatigue assessment of the net members and the pod membrane. There is minimal published data on the fatigue of membranes but TTI's knowledge of the fatigue of fibre ropes was applied (the reinforcing cords are the same material and of a similar twisted construction but just at small scale). Good data exists for the fatigue of synthetic fibre ropes (e.g. DNVGL-OS-E301). Using measured tank test data, the derived design factors for maximum tensions in the meridionals, the DNV code, and a representative environment (North Atlantic e.g. offshore west Orkney), the fatigue analysis showed that the net elements should have a conservatively estimated life into the hundreds of years. The FEED work culminated with a detailed specification for a full-scale Stage 3 system, for the pod, net ropes and net junction components and following a brief detailed design phase this could proceed to manufacture at Stage 3, with high confidence.

In summary then, the Stage 2 project achieved all objectives set out at the project inception and we are on track with the technical development roadmap. These objectives were specifically designed to "hit" the residual risks at the end of the Stage I project. Through the work carried out all the residual risks have been totally or largely mitigated. The flexible buoyant pod has been shown to behave as a rigid body when inflated to operating pressure, in both analysis and test. The variability in net tensions has been assessed stochastically and a meridional design factor developed. The dynamic tensions in the net have been assessed and a thorough fatigue analysis carried out that shows exceedingly long life, much greater than typical deployment lives. The buoyant pod is deemed to be similar and this shall be the focus of actual fatigue testing on material tokens at Stage 3. The abrasion testing has highlighted preferred material choices for the external layer of the pod, and these have been shown to be exceedingly abrasion resistant under full-scale contact pressure and highly accelerated sliding distances. The net junction capacity has been assessed and a novel solution developed to enhance this.

1.4.2 Cost Assessment

The costing assessment of the NetBuoy100 was based on the outputs of the Stage 2 FEED which provided a NetBuoy system specification which could be compared against the steel equivalent. The steel buoy and steel sub-systems on the NetBuoy (e.g. machine room) had already been designed and costed as part of the Stage 1 FEED. The comparable steel buoy structure is in the 40-tonne range to achieve the required strength and rigidity. The equivalent steel mass is regarded as being high certainty as the equivalent structure has been designed according to DNVGL ship design rules in concord with Black and Veatch. The NetBuoy costs were revisited for Stage 2, following the completion of the FEED. High certainty costs were derived for NetBuoy sub-systems. Net costs were based on manufacturing assessment by TTI and latest rope costs. Buoyant pod costs were based on up to date quotations from Ship-to-Quay (STQ) fender manufacturers. Estimates were also supplied for cost of ballasting and inflation systems unique to the NetBuoy and steel based buoy. Transportation, installation and O&M costs were based on numbers output from a study by Quoceant. The cost benefits between the NetBuoy and steel buoy remain largely unchanged since Stage 1.

In terms of CAPEX for buoy manufacture:

- the NetBuoy with integrated machine room is less than 60% the cost of the equivalent steel buoy.
- the NetBuoy without integrated machine room is less than 30% the cost of the equivalent steel buoy.
- both configurations satisfy the target of £1 million pounds CAPEX per MW installed capacity (refer to Figure 19).
- the largest portion of the cost saving of the NetBuoy comes from the reinforced elastomeric material.

In terms of CAPEX association with transportation and installation:

- the NetBuoy with integrated machine room is less than 60% the cost of the equivalent steel buoy. This is projected to reduce to less than 30% with mass installation learnings.

- the NetBuoy without integrated machine room is less than 20% the cost of the equivalent steel buoy. This is projected to reduce to 10% with mass installation learnings.

In terms of OPEX:

- Largely due to the ability to install the NetBuoy in higher limited sea-states, it is estimated availability figures can be increased by 5%-10%.
- If the design life of the NetBuoy is extended to 20 years which is wholly realistic, with low probability of failure this will lead to significant annual O&M savings.

CAPEX and OPEX cost benefit translated to significant improvements in levelised cost of energy. LCOE was estimated using the supplied WES LCOE tool, which provides a typical cost breakdown for non-prime mover cost centres. No attempt has been made to design and cost the other subsystems such as anchor, mooring tether and PTO, although relative costs have been adjusted to reflect improved transportation and installation costs and improved availability.

In terms of LCOE this has only been compared, using the WES tool, between the NetBuoy and steel buoy for integrated machine room, as cost of installing the machine room on seabed has not been calculated for this project and is considered to be uncertain with high variation depending on WEC technology, site conditions and anchoring solution:

- For the integrated machine room case the NetBuoy LCOE is estimated to be £155 per MWh. Which compares to £227 per MWh for the steel equivalent.
- If projected mass installation learnings rates are enabled, then the LCOE for NetBuoy with integrated machine room reduced to target £150 per MWh.

In terms of reducing the LCOE for the NetBuoy in its current guise or when applied to other WEC architecture a number of avenues and levers have been identified to reduce the cost of energy further.

Overall residual technical and cost risks have been compiled and re-ran through the qualification planning process to generate a work plan for a potential Stage 3 project and the key recommendations for further work are presented in section 1.7.

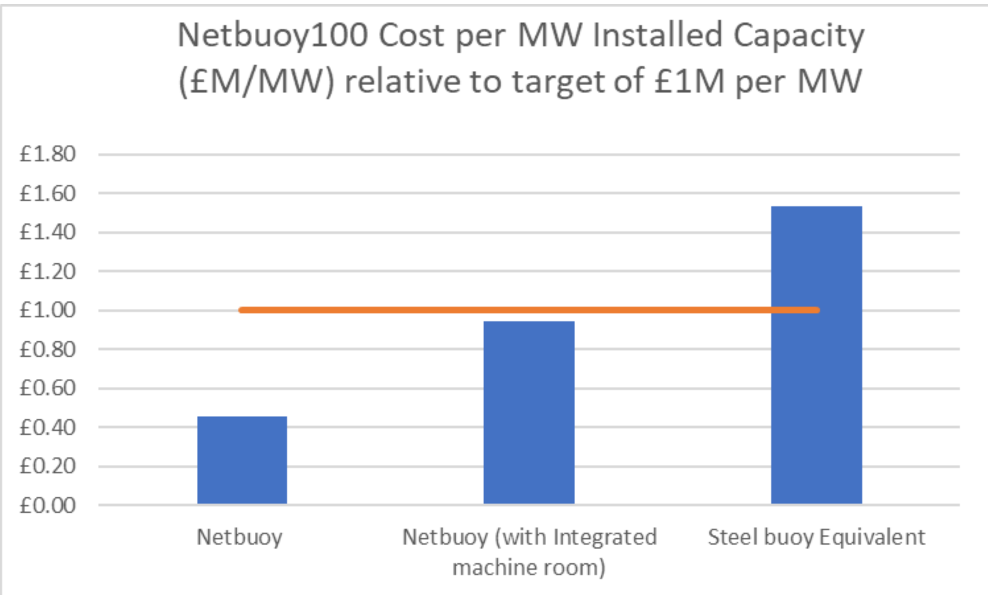

Figure 19: CAPEX for prime mover comparing NetBuoy configurations with Steel Buoy (assuming steel buoy has integrated machine room)

1.5 *Applicability to WEC Device Types*

TTI along with B&V conducted a review of the applicability of the NetBuoy to other WEC devices. Applicability to other WEC types was a key activity in the NetBuoy 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. Since Stage 1, TTI have also been exploring a number of promising avenues with WEC developers, whilst looking at the application of the technology within the wider offshore renewables and marine sectors.

Table 2: Applicability to other WECs

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 while 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.
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 movement 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. An 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 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.

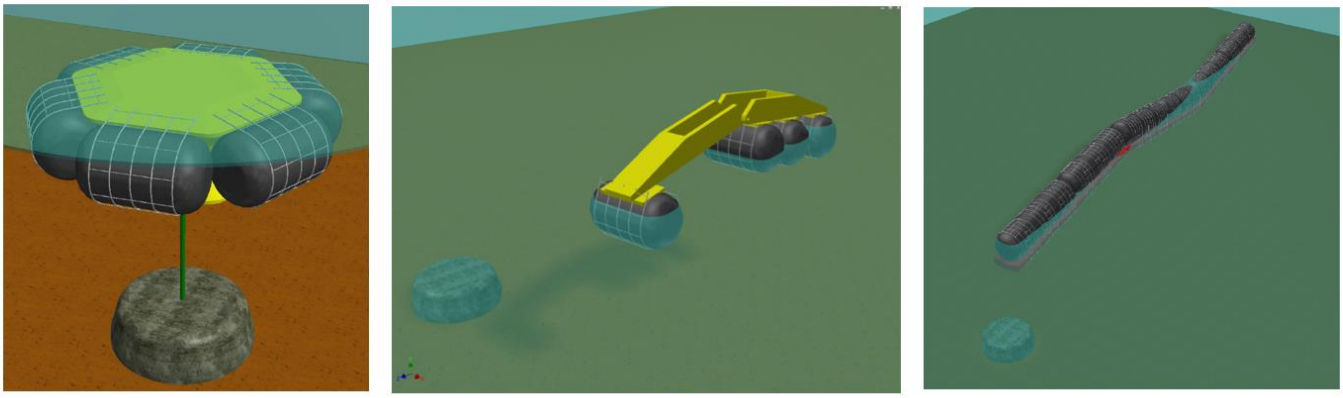

Figure 20 – Schematic of NetBuoy technology being applied to different WEC architectures

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 2 has been completed. To date, public dissemination has largely been via WES wave energy conferences. We look to build on this.

1.7 Recommendations for Further Work

As part of TTI's overall qualification plan (in concord with DNVGL-RP-A203 – Qualification of Novel Technologies) a detailed programme of work has been outlined and costed for Stage 3, to further increase technology and commercial readiness levels of the NetBuoy system and mitigate any residual risks from Stage2.

It is proposed that the next phase of work will include large elements of field and laboratory material testing.

It is proposed that TTI will conduct intermediate scale field testing of the NetBuoy which will significantly increase confidence in terms of:

- Larger scale system design and build of net and integration with buoyant pod.
- Air holding.
- General handing of object of this size and mass.
- Marine operations including initial deployment and inflation.
- Medium-term response to environment including relative motion between pod and net, UV and ozone and biofouling.

Although the test environment is no longer controlled, the system is large enough to allow much more line tension instrumentation to be utilised. It is proposed to measure:

- Meridional tensions at bottom of net in every meridional simultaneously.
- Attempt to measure circumferential tensions.
- Internal pressure.
- Qualitative submerged shape observations.
- Post-test line residual strength measurements (break test).
- Post-test dissection and examination of pod laminate.

The field test will be complemented with controlled laboratory fatigue testing of material samples, while also developing material repair and maintenance strategy and conducting repair trials. It is also proposed that further tank testing will be conducted to demonstrate the applicability of the NetBuoy technology on other WEC concept designs and therefore improve the commercial readiness of technology to the wider industry.

Beyond testing TTI will conduct further design and modelling which relate to validation of material behaviour under extreme and fatigue loading, further develop the FEED for commercial WEC and develop design tools that will be used to provide decision making guidance for developers wishing to utilise the NetBuoy system.

LCOE analysis has been carried out at both Stage I and Stage 2 and this will be extended into the Stage 3 project. As technical and commercial readiness increase through the projects the certainty in the cost estimates increases also and the LCOE in turn shall be more certain. TTI will also further develop the commercial exploitation plan and refine the commercial roadmap, while fostering relationships with the supply chain and considering requirements of commercial scale production.

With the proposed test schedule and engineering design activities the remaining residual risks shall be further reduced in severity and the system will be deemed to have advanced to greater TRL and be ready for integration into WEC systems and commercial roll-out.

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. TTI-TM-2019-7827-R1005-Rev00 FINAL TECHNICAL REPORT AND FEED (**Confidential**)
3. www.tensiontech.com (website will be used to promote NetBuoy in the future)

2 Publicity Material

Filename	Media Type	Description
WESAC19 poster NetBuoyII TTI (A32286549) rev3	pdf	Poster for WES conference 2019
1500hrs_TTI_Yeats_NetBuoy_SMMP Rev1.pdf	PowerPoint	Presentation for WES conference 2019