netbuoy™

TTI Marine Renewables

WES Structural Materials and Manufacturing Processes Stage 3 Public Report

Tension Technology International Ltd

This NetBuoy project has been supported by Wave Energy Scotland

1 Project Outputs

1.1 Project Introduction

This is the final public report for the NetBuoy project which was funded by Wave Energy Scotland (WES) under the Structural Materials and Manufacturing Processes (SMMP) Programme. Where appropriate this report also provides a recap of Stage 2 outcomes, which were used to inform the Stage 3 technology qualification plans. All NetBuoy public reports (Stage 1 to 3) are available on the Wave Energy Scotland website [1].

The Stage 3 project was the natural follow-on from the Stage 2 project, the activities proposed and conducted in Stage 3 having been informed by the residual technical risks and the ensuing qualification plan formed at the end of the Stage 2 project. The overall aim of the Stage 3 project was to progress the system to a high TRL (Technology Readiness Level) and to demonstrate NetBuoy's suitability for integration into a commercial scale wave energy collector (WEC). To achieve this, the qualification tests in Stage 3 included, extended sea trials of a NetBuoy system, laboratory material and fatigue tests, and further scale-model tests to demonstrate the applicability of the NetBuoy system to other WEC architectures. Further development included design engineering activities and further improvement in the cost of energy, which was already demonstrated to be attractive at the end of Stage 2. More information on the NetBuoy system can be found on a dedicated website [2], which includes a design tool for WEC developers to assess the suitability of and cost estimate for a NetBuoy base prime mover when integrated into their wave energy technology of interest.

The NetBuoy project encompassed two areas which Tension Technology International Ltd (TTI) sees as being key to the path towards cost competitive wave energy:

(i) impermeable fabrics to provide compliant and thus load shedding (peak load resistant) buoyant pods; and
(ii) fibre rope 'load nets' to encapsulate the buoyant pods, 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 elastomeric buoyant pods as they cannot easily be restrained otherwise – the restraint must be distributed over the surface of the buoyant pod.

This combination of elements to provide the prime mover of a WEC significantly reduces the overall structural mass (compared to an equivalent steel structure) through two mechanisms. Firstly, the typical density of the materials is around one-seventh that of steel. Secondly, the materials are much more compliant, with the achievable strain at break typically ranging from 2% for the stiffest materials such as high modulus Dyneema, to 20% for nylon, and upwards into hundreds of percent for elastomers and rubbers. This compares to steels where the elastic limit is typically set to 0.2%. This compliance is inherently 'load-shedding' as the structure is compliant to peak loads and requires much less material to survive peak

1 https://library.waveenergyscotland.co.uk/
2 https://www.netbuoy.co.uk

loads [3]. The inflatable nature of the prime mover also affords significant advantages at the manufacturing, transportation, and installation phases.

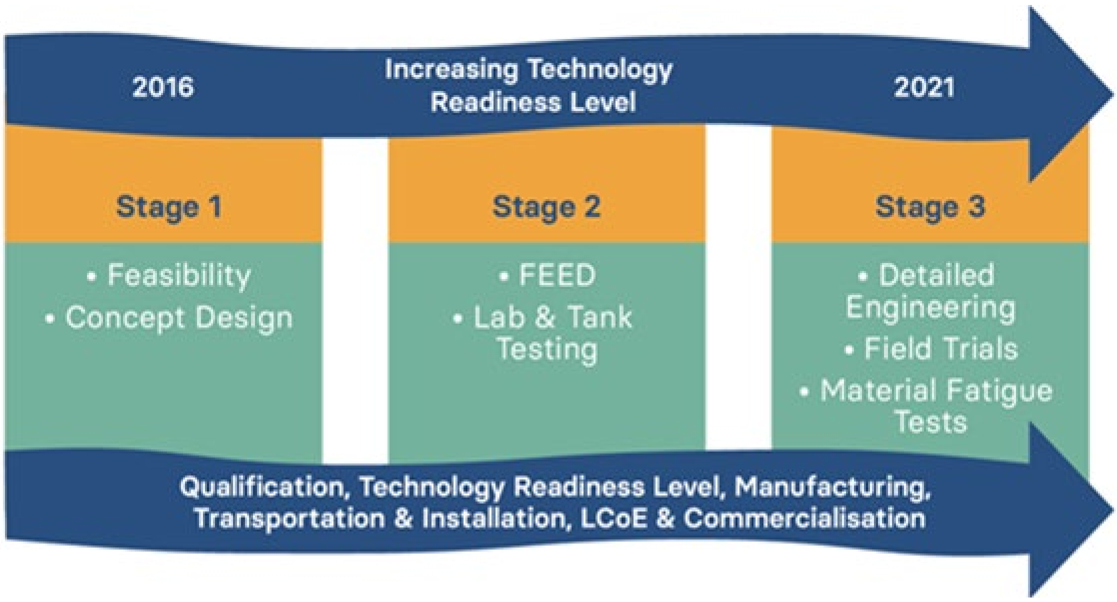
The WEC technology case study for this project has been a generic ground referenced heaving point absorber [4]. A medium-sized NetBuoy (termed NetBuoy100) was chosen for detailed engineering and cost assessment in Stage 2 and benchmarked against a steel equivalent buoy to demonstrate the cost benefits and potential impact on levelised cost of energy (LCOE), using the WES costing tool. TTI consider two configurations of NetBuoy100: (1) assuming a remote machine room located on the seabed; (2) assuming a machine room that is integrated and forms part of the NetBuoy100 (see Figure 2). The NetBuoy100 is also considered for the cost of energy case study in Stage 2 and 3.

1.2 Overview of Stages 1 – 3

Stages 1 & 2 are reported in previous public reports; however, a brief overview of prior work is provided to aid the context of Stage 3.

The NetBuoy system has undergone a staged development programme (Figure 1).

Figure 1: Staged Development Overview



1.2.1 Stage 1 – Feasibility and Concept Design

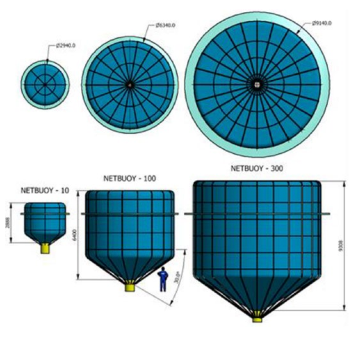
Stage 1 demonstrated the excellent cost-benefit and technical viability of NetBuoy compared to a steel-based equivalent prime mover. A comprehensive landscaping and design engineering study was conducted. Manufacturability and ease of installability were used to inform the economic model. Finite element analysis (FEA) and Orcaflex modelling of early designs informed the best buoy shape for material stress distribution and net load distribution. A key part of Stage 1 was developing a WEC technology case study; a generic ground referenced heaving point absorber was selected. 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-

[3] Steel structures are essentially strain limited (required to keep deflections at peak load below the 0.2% elastic limit) which requires more material to provide the stiffness. Without needing stiffness to maintain very low strains much less material can be used with synthetic structures.

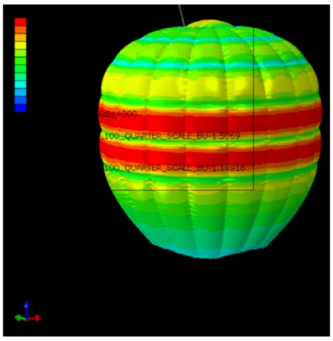
[4] Section 1.6 of this report details the applicability of NetBuoy to other WEC architectures.

sized NetBuoy100 was ultimately selected for more detailed engineering and cost assessment in Stage 2 and Stage 3. The NetBuoy100 was calculated to have a nominal rating of 150kW. A systems engineering approach was adopted, together with developing a basis of design and a technology qualification plan (in accordance with DNV-RP-A203), which was used to inform qualification test and engineering research priorities at each subsequent phase. The NetBuoy prime mover CAPEX was benchmarked against an equivalent steel structure designed according to DNVGL ship design rules by Black and Veatch.

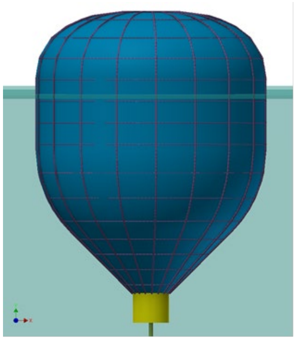
Figure 2: Examples of Stage 1 Development



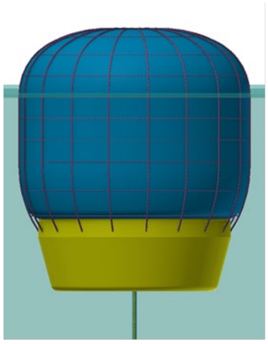
NetBuoy10, NetBuoy100, NetBuoy300 – early concept development (pre-FEA)



Non-linear FEA validated against Stage2 tank tests



NetBuoy100 with remote machine room

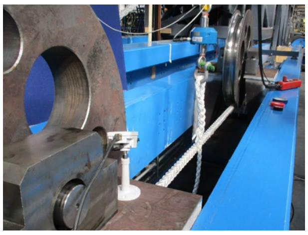


NetBuoy100 with integrated machine room

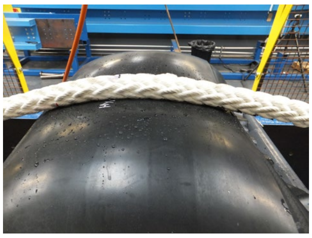
1.2.2 Stage 2 – Qualification Tests

A key aim of Stage 2 was to deliver the qualification tests and mitigate technology risk via the systems engineering approach outlined in Stage 1. TTI continued to adhere to the recommended practice for the qualification of novel technology (DNVGL-RP-A203). Stage 2 involved scaled full-system manufacture and wave tank testing together with full-scale subsystem and component testing (e.g., rope abrasion trials on candidate elastomer material samples). Data acquired from these tests were used to correlate and update the numerical and FEA models developed under Stage 1. Design methodologies and manufacturing and installation know-how were then applied to optimise the design and update the levelised cost of energy and commercialisation.

Figure 3: Examples of Stage 2 Development



Net junction testing



Abrasion testing – rope on candidate elastomers

Hydrostatic tank tests – ¼ scale

Survival tank tests – 15th scale

1.2.3 Stage 3 – Field Test

The primary focus of Stage 3 was field prototype testing and laboratory material property testing. A secondary focus was further wave tank testing to demonstrate the applicability of NetBuoy to alternative wave energy system architectures, and to investigate the applicability of NetBuoy to other marine sectors.

A NetBuoy prototype was designed, manufactured, and installed in the Cromarty Firth in November 2020 for a 6-month deployment period. A commercial off-the-shelf (COTS) Yokohama marine fender was used to represent the NetBuoy buoyant pod. This measured 2.5m in diameter by 4.0m in length and was considered an ideal representation of the buoyant pod [5].

The purpose of the field trial was to demonstrate handleability and installability and mitigate those residual risks from Stage 2 that could only be addressed by installing a large system in a real environment. Learning from the field trial includes the propensity to accumulate biofouling, environmental degradation and interactions between the 'Net' and the 'Buoy' subsystems. Further detailed biofouling studies involving several candidate rubbers were conducted by Heriot-Watt University. Samples were deployed at EMEC's Scapa Flow site for a period of 6 months.

Stage 3 is described in more detail in subsequent sections.

1.3 Description of Project Technology

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 buoyant pods and fibre rope encapsulation nets.

Recognising that many 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., 80kPa for a 6m diameter pod) the pod is exceedingly rigid (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 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.

Wave tank testing in Stage 2 has demonstrated that no mechanism exists to induce large increases in internal pressure; the internal pressure varies only modestly under the wave action, so the dynamic strain range is small. With a 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 operational life of a WEC. Indeed, a fatigue life of hundreds of years is expected, showing a large design fatigue factor. This has been verified in the Stage 3 fatigue tests on material samples taken from a new marine fender (discussed further in subsequent sections)

Despite being globally rigid and with low overall strain range under severe wave impacts, the system is 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 steel's 0.2% elastic strain limit is exceeded even when thick (and hence heavy and expensive) plate is specified for this reason.

5 Stage 2 manufacturing studies had concluded that a vulcanized reinforced rubber pod was the best approach as a mature supply chain exists for marine fenders and existing tooling could be exploited.

This highlights the structural inefficiency of steel hulls for WEC applications where the hull mass is driven by rare extreme events and the cost is high because of this.

Further important benefits of the inflatable buoyant pod over equivalent rigid structures include the ease of transportation and installation. The low weight benefits handling, transportation, and installation generally. In an uninflated form the buoyant pod can easily be packed and transported in standard containers unlike an equivalent rigid structure which must be transported to site in its final form. Containerised transport opens cheaper supply-chain options. Installation may also be facilitated via partial inflation of the buoyant pod at the point of hook-up.

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

The key system level engineering challenge with a membrane buoyant pod is attachment to the remainder of the WEC system. With a rigid hull, this is largely straightforward 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 '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), or ship-to-quay (STQ), pneumatic fenders. These 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 during Stage 2 and options do exist for variants [6].

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. Finished nets are easily and compactly containerised for transport to the final assembly location.

In summary, the innovation pursued with NetBuoy is the system integration of flexible membrane buoyant pods (which are well known) and fibre rope nets (which are also well known) into a cohesive system for the provision of buoyancy, water plane area and displacement for WECs. Within the overall NetBuoy system numerous "small" innovations are also utilised such as net connectors, manufacturing methods, shape definition and so on.

1.4 Scope of Work

The overall aim of the Stage 3 project was to advance the system to high technical and commercial readiness to provide confidence in the system and materials for future integration into commercial-scale WEC technology. The specific activities were informed by the residual technical risks identified at the end of Stage 2 and the ensuing engineering and testing qualification plans were designed to mitigating these technical risks. The objective was to ensure sufficient confidence was accumulated in readiness for a future

[6] For example, lay-up over an inflated mould (as opposed to inside a rigid mould) and then performing hot consolidation or vulcanisation. This kind of process is utilised for marine air bags and STS fenders that are not certified to ISO17357-1.

Stage 4 project (e.g., a first grid-connected commercial-scale WEC utilising NetBuoy technology for a prime mover).

The key Stage 3 work packages were:

- **Laboratory material fatigue testing**: these tests were important to generate high-quality data on the fatigue response of reinforced elastomer materials. Ultimate tensile load testing was also conducted. These tests were performed at the Energy Technology Centre, near East Kilbride, Scotland.
- **Extended soak testing in marine environment**: this activity addressed several technical risks that could only be de-risked by deploying a large-scale system in a real environment. While field testing introduces a loss of control (relative to tank testing), the system is deployed for much longer and is subjected to a representative range of environment forces and degradation. The NetBuoy was deployed in the Cromarty Firth, Scotland, for a 6-month period to help understand biofouling, the response to exposure to UV light and ozone, interactions between the net and buoyant pod, and to provide learnings relating to manufacturing, assembly, and installation. On recovery, the buoyant pod underwent a quayside drop test to qualitatively simulate and assess an extreme wave impact event [7]. A separate biofouling trial was performed by Heriot-Watt University at EMEC's Scapa Flow nursery site in which candidate materials were deployed for a 6-month period.
- **Post soak material assessment**: the "soak" test in seawater gives a significant amount of learning and risk reduction but further value is secured through a robust post-deployment assessment. Residual strength tests were conducted on net rope samples and elastomer samples cut from the buoyant pod. A forensic examination of the aged components provided evidence on the degradation mechanisms.
- **Small scale testing of alternative WEC forms**: this work was primarily to increase the commercial readiness by proving the TRL for the NetBuoy system when applied to different WEC forms. This work complemented an online design tool that was developed to allow WEC developers to assess the applicability of the NetBuoy to different WEC forms (this is discussed in more detail in section 1.6). These tests were conducted in the Kelvin Hydrodynamic towing/wave tank at a nominal 6th scale. The ¼ scale model of the NetBuoy100 tested in Stage 2 was returned to the tank with all meridional net lines instrumented to better understand the distribution and statistical variation of loads within the net.

In parallel to the qualification tests and further engineering development, the LCOE was revisited, and further manufacturing assessments were conducted. Technology and commercialisation roadmaps were also development as part of a NetBuoy exploitation plan.

Examples of the qualification tests conducted in Stage 3 are shown in Figures 4 to 14. Project achievements are summarised in section 1.5.

[7] The buoyant pod was dropped from height onto the still water surface adjacent to the quayside. The drop height was calculated such that the pod's velocity at impact was the equivalent of the water particle velocity in an extreme wave impact event.

Examples of Stage 3 Qualification Tests

Figure 4 Elastomer samples used for fatigue tests

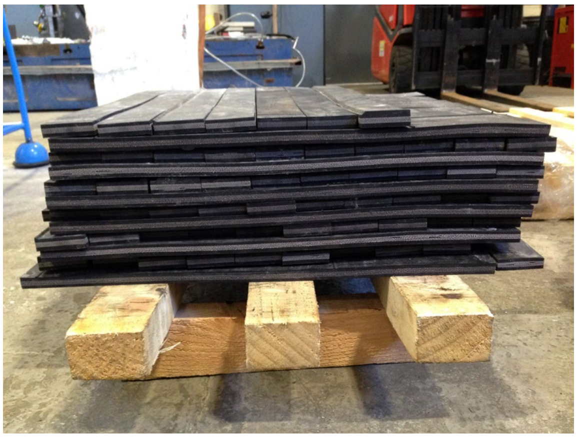


Figure 5 Fatigue testing sample

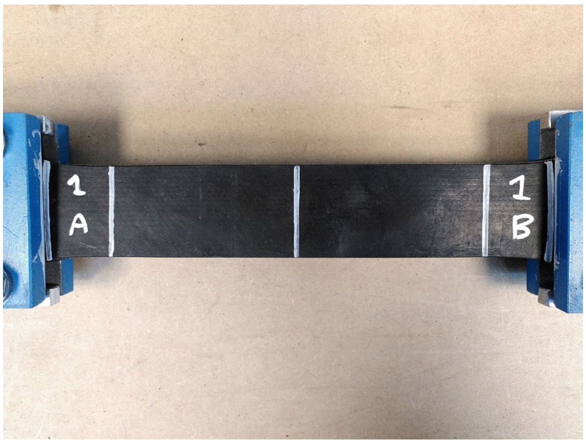


Figure 6 Fatigue testing rig

Figure 7 Post soak residual strength test (rope)

Figure 8 NetBuoy deployment in the Cromarty Firth

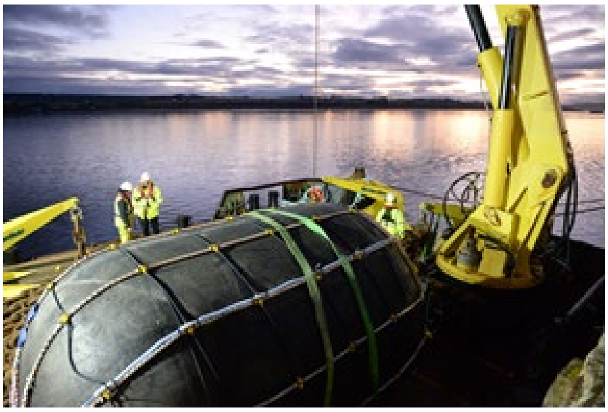


Figure 9 Cromarty Firth soak test deployment

Examples of Stage 3 Qualification Tests

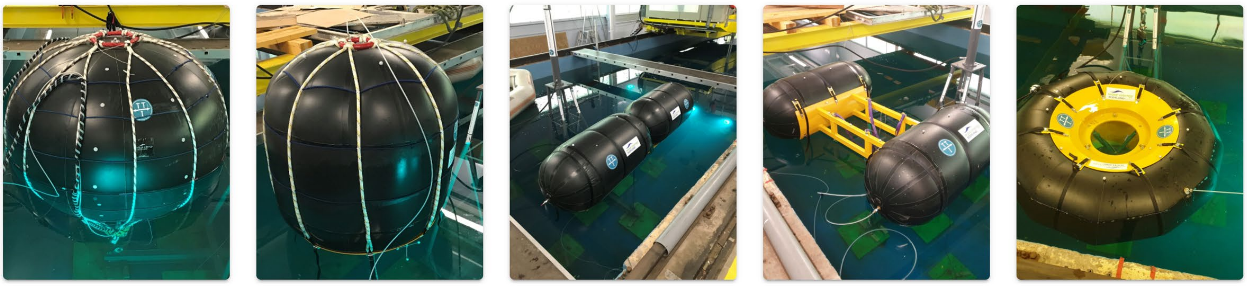
Figure 10 Preparing for drop test

Figure 11 Drop test impact

Figure 12 Heriot Watt University's biofouling test rig with NetBuoy candidate and control materials (pre-depoyment)

Figure 13 Deploying the biofouling rig at EMEC's Scapa Flow site

Figure 14 Alternative WEC forms tested in the Kelvin Hydrodynamics Laboratory



1.5 Project Achievements

Overall, the NetBuoy project achieved its goals. This was largely aided by following a structured system engineering approach across all stages of the programme. Being an R&D exercise, this is always a somewhat complicated exercise. Work packages have been defined using a risk-analysis approach with activities and tasks designed to address and mitigate the key technology risks at stage. All planned qualification tests were successfully completed. The residual risks from Stage 2 were largely mitigated in Stage 3 and encouraging outcomes generated.

1.5.1 Stage 2 – Qualification Tests (recap)

The manufacture of the quarter-scale system was an extremely useful process. As with any scale model limitations exist. It was not possible to make a fully vulcanised buoyant pod [8] 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 a 1.6m diameter pod, providing a total enclosed volume of around 2.7m^3. The pod was made from 12 gores (panels) of fabric, cut to shape according to TTI's developed patterns. The finished pod matched the specified design shape extremely well with wet testing showing the displaced volume at nominal draught to be 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, and the effect of ambient conditions. It was found that the air leak rate was less than 1% of volume per day, this is achieved 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 unique selling points of the system. The pod, weighing only a few kilograms, arrived in a small cardboard box and was easily carried into the building by one person. The pod was quickly assembled into the net and after a few minutes of inflation a NetBuoy with nominal 2 tonnes displacement had been created. No other form of buoyancy (steel, concrete, HPDE etc.) could possibly fulfil this function.

In further wet testing, the quarter-scale buoy underwent a series of quasi-static tests to ascertain shape change in response to varying internal and external pressures. This demonstrated that the pod acted as a rigid body once internal pressure exceeded the hydrostatic pressure at the maximum submergence, with indiscernible volume change with respect to variation in external pressure head. Motion tracking markers on the membrane were used to measure shape change during these tests. The water plane diameter was found to vary less than 0.5% over a very broad range of pressure differentials.

Tests with the one-fifteenth scale model addressed similar aspects but with a dynamic wave field applied. The internal pressure was found to vary modestly with external wave action 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. Although the measurements were somewhat uncertain, they did provide an insight of the variation along the length of a single meridional due to friction against the pod and the day-to-day variability due to changing set-ups. This led to the development of a stochastic analysis to better understand the likely variability.

Rope-on-pod abrasion testing was another key de-risking activity identified in the qualification plan. The test rig used inflated ‘pillows’ to best represent the contact condition between the rope and pod. Five different elastomer samples were bonded to the pillow surface and a full-scale tensioned rope was cycled back and forth over the sample. In terms of total slippage, this was a highly accelerated test due to the enforced sliding distance. The selected rope turning diameter (i.e., surface curvature) enforced by the

[8] Tooling costs were prohibitively expensive for manufacturing a one-off item.

inflated pillow shape and the rope tension resulted in an average contact pressure (average over the rope diameter/width) that was very close to the expected full-scale system value. The pillows did make the test setup more challenging. On every cycle, the pillows underwent global shearing motions prior to the rope sliding. However, care was taken to ensure that the sliding distance was comparable for every sample tested. The measured wear volumes (in the elastomer samples) showed some elastomer materials to be excellent in abrasion performance and some to be very poor. The rope was largely untroubled by the sliding.

The performance of a full-scale net joint was tested. The joint was single cruciform net junction consisting of a single meridional (main) rope held horizontally under tension with a single circumferential rope pulled vertically through meridional rope, forming a plain net joint. Wet testing had identified the most important design case for joint "locking" was when the system is not pretensioned. Without pretension the plain net joint can easily slip. While this is desirable for manufacturing and initial assembly, it is preferable to have it locked during a deployment to prevent the net geometry changing. When under tension, the meridional lines have a "self-locking" function at the net joint due to inter-strand friction in the rope [9]. Several variants were trialled before a preferred solution was identified. The preferred solution can quickly, easily, and cheaply impart joint reinforcement in the un-tensioned condition and 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 of 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 one-offs. A hybrid manufacturing approach was also assessed in detail that does not require a metal mould. While this is attractive for low-volume manufacture, further process de-risking is required, and this is identified. In addition to the manufacturing studies, the FEED activities detailed ancillary components required and carried out detailed fatigue assessment of the net members and the pod membrane. While there is minimal published data on the fatigue of membranes, good data exists for the fatigue of synthetic fibre ropes (e.g., DNVGL-OS-E301) [10]. Applying TTI's knowledge of fatigue in fibre ropes, a fatigue analysis showed the net elements to have a conservatively estimated life in the hundreds of years (based on measured tank test data, the derived design factors for maximum tensions in the meridionals, the DNV code, and a representative operational environment for the North Atlantic, e.g., offshore west Orkney). The FEED work culminated with a detailed specification for a full-scale NetBuoy system (i.e., the pod, the rope net, and the net junction components) and following a brief detailed design phase this could proceed to manufacture in Stage 3, with high confidence.

In summary, the qualification activities achieved the Stage 2 objectives and the technical development roadmap for the NetBuoy concept remained on track. The Stage 2 objectives were specifically designed to "hit" the residual technology risks identified at the end of Stage 1. These residual technology risks have been largely mitigated through Stage 2 activities. The flexible buoyant pod has been shown to behave as a rigid body when inflated to operating pressure, both in analysis and under 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,

[9] This is much like a conventional eye splice which achieves sufficient internal locking to provide full rope break load capacity.

[10] The reinforcing cords are formed from the same material and are of a similar twisted construction, just at small scale.

much greater than the typical WEC deployment life. The buoyant pod was deemed to be similar [11]. 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.

1.5.2 Stage 3 – Qualification Tests

Extended Soak Test

The NetBuoy deployment in the Cromarty firth was a "full-lifecycle" test and was expected to inform aspects of device design and build, deployment and installation, normal operations, and recovery. In addition, it was expected to glean learnings in terms of the tendency to accumulate biofouling and observe material effects due to the exposure to seawater, ozone, and UV. The NetBuoy system successfully survived 6 months of testing in a real environment from winter through to early summer, experiencing a range of metocean conditions: maximum significant wave heights of around 0.5m; 40 knot winds; and currents of several knots.

The net around the top hemispherical end of the buoyant pod displayed no change in position with respect to the pod over the duration of the test. This is an important finding since large relative movements could be expected to exacerbate any wear at the pod-net interface and this has not manifested.

ROV inspections showed the net terminations and connection to the rigid node (and in turn to the mooring system) performed as expected and required. Post-test examinations showed no signs of distress to these steel components and that the low-specification paint system performed better than expected.

On recovery the NetBuoy was surveyed by biofouling experts from Heriot-Watt University. The net was removed and inspected, and samples taken for residual strength testing. The buoyant pod was jet washed and inspected. The outer layer of the buoyant pod showed no significant damage or distress. The buoyant pod demonstrated its resilience to physically handling during deployment and recovery, only showing evidence of minor damage in the form of minor surface scratches and scuffs.

Post-test dissection of the buoyant pod found that a minimal quantity of water had accumulated in the pod. This could be entirely attributed to the water content of the air introduced to the system.

Various lessons were learned during the assembly, installation and recovery of the device largely related to the tools and equipment used rather than the NetBuoy itself.

In summary, the extended soak test was completed successfully and demonstrated the full system integration of buoyant pod and load restraint net in a real-sea environment.

Drop Testing

Quayside drop tests of the NetBuoy buoyant pod system were performed to demonstrate the pod's survivability under breaking wave impacts in extreme wave conditions. The drop height was specified to achieve an impact velocity commensurate with wave impact velocities expected during extreme breaking

[11] This was identified as a key residual risk at the end of Stage 2 and fatigue testing of the buoyant pod membrane material was a qualification activity at Stage 3.

wave events at highly energetic wave energy sites. Impact velocities of just under 20 m/s were achieved with the maximum available drop height. Numerous drops were performed [12].

Minor global and local elastic deflections were observed in the pod structure during impact. Upon inspection no damage attributable to the drop testing was observed. This demonstrated the pod's excellent characteristics in enduring extreme impact events without damage or plastic deformation.

Key outcome: The inflated buoyant pod is resilient in extreme wave impact events. No design change is suggested or required.

Material Residual Strength Testing

At the conclusion of the extended soak test, the buoyant pod was dissected for examination and material residual strength testing. Tensile tests, conducted on three samples, indicated the material had suffered minimal degradation, retaining a considerable proportion of its strength.

Similarly, the ropes forming the meridionals of the net sub-system were removed for examination and testing. In general terms the ropes were in good to excellent condition with the only significant degradation being due to external handling abrasion damage, not damage accumulated during the operational phase. It was concluded that rope strength was not significantly denuded through wear or fatigue and as such the ropes were well selected for the application by the design principles developed at Stage 2. Importantly, it is expected that these ropes could remain in service for a much longer duration with no concerns.

Other components of the net sub-system were all in good condition and performed as required.

Key outcomes: The membrane was fit for purpose. The buoyant pod membrane demonstrated a large percentage of the estimated break-strength (within the limits of the test equipment), and it is judged that minimal degradation-in-service occurred. The ropes did not suffer much degradation through testing and the rope selection principles developed in Stage 2 were appropriate.

Material Fatigue Testing

Fatigue failure of the reinforced rubber membrane of the buoyant pod was identified as a high risk in the Technical Risk Register. As identified at Stage 2, there is currently little to no data on the fatigue response of reinforced elastomer materials. A testing program to generate high-quality high-certainty data on the fatigue response of a reinforced rubber membrane was designed by TTI to further the understanding of the material and mitigate the identified technical risk. The tests were conducted at the Energy Technology Centre, East Kilbride, Scotland.

An ε-n curve was developed utilising eight samples for every test parameter. The ε-n curve showed that the reinforced rubber membrane has a fatigue life significantly higher than NetBuoy would expect to experience during operation. At the anticipated operational strains, the reinforced rubber membrane is predicted to have an exceedingly long fatigue life of more than five billion cycles. The original technical risk is mitigated with a very low residual risk priority.

Residual strength testing showed the reinforced rubber membrane had suffered no detrimental effects and no strength loss due to fatigue cycling after two million cycles at typical operating conditions. The two million cycles were judged to be equivalent to at least 5 years of real-world load cycling.

[12] Footage of the drop tests can be viewed on TTI's YouTube channel https://www.youtube.com/channel/UCVxlqGHg1JtNBg7qXt0ypuQ

Key outcome: Reinforced elastomer laminate is exceedingly fatigue resistant at low strain ranges. Even at higher strains (unrealistic strains in expected operational conditions) the material can accept millions of cycles. No fatigue testing of the net rope elements was necessary as TTI possesses a wealth of inhouse test data from our own testing laboratory that confirm their suitability in terms of fatigue life.

Biofouling

Heriot-Watt University (Orkney Campus) [13] was engaged to perform two parallel biofouling studies

(i) quantitative tests of candidate elastomer samples at EMEC’s Scapa Flow wave site, Orkney using their proprietary biofouling test rig.
(ii) qualitative assessment of the biofouling accumulation on the NetBuoy during the Cromarty Firth deployment.

Both studies covered the 6-month period from early winter 2020 to early summer 2021.

For the quantitative Scapa Flow study, TTI shortlisted three candidate elastomer materials (including polyurethane) together with a control sample of HDPE (High Density Polyethylene). The control sample enabled comparison with previous studies. The Heriot-Watt team used established testing protocols, which required the periodic removal and replacement of sample panels. On removal, each sample panel was analysed and assessed for marine growth and its weight recorded.

The qualitative Cromarty Firth study was based on periodic ROV surveys of eight designated vertical zones delineated by the net ropes. The study concluded with a final survey on recovery of the NetBuoy.

The Scapa Flow study indicated the relative performance of the candidate materials providing useful information on material selection and mitigation strategies. It was found that the conventional outer rubber used on NetBuoy performed no better or worse than the other similar materials (in terms of biofouling accumulation propensity). While its adoption for future deployments appears justifiable, care should be taken to ensure the inherent biofouling rate is acceptable. This could depend on the specific deployment location.

Where a specific structure or area requires enhanced biofouling protection, the application of a polyurethane elastomer coating can minimise biofouling accumulation. A polyurethane coating renders the surface easier to clean and imparts excellent abrasion resistance.

1.5.3 Cost Assessment

The cost assessment of the NetBuoy100 buoyant pod in Stage 2 was based on quotations for equivalent commercial off-the-shelf (COTS) marine fenders. In Stage 3, the cost assessment has been based on verified engineering principles, developed in Stage 2, for a more optimised material lay-up of vulcanised reinforced elastomer which could be adopted for medium volume production. Both approaches lead to a CAPEX which is superior to the steel-based equivalent prime mover.

Previous cost assessments of the net sub-system were already considered to have a high certainty given TTI’s experience in the design and manufacture of nets for other marine applications

[13] Heriot-Watt University has extensive experience in the assessment of biofouling on marine structures.

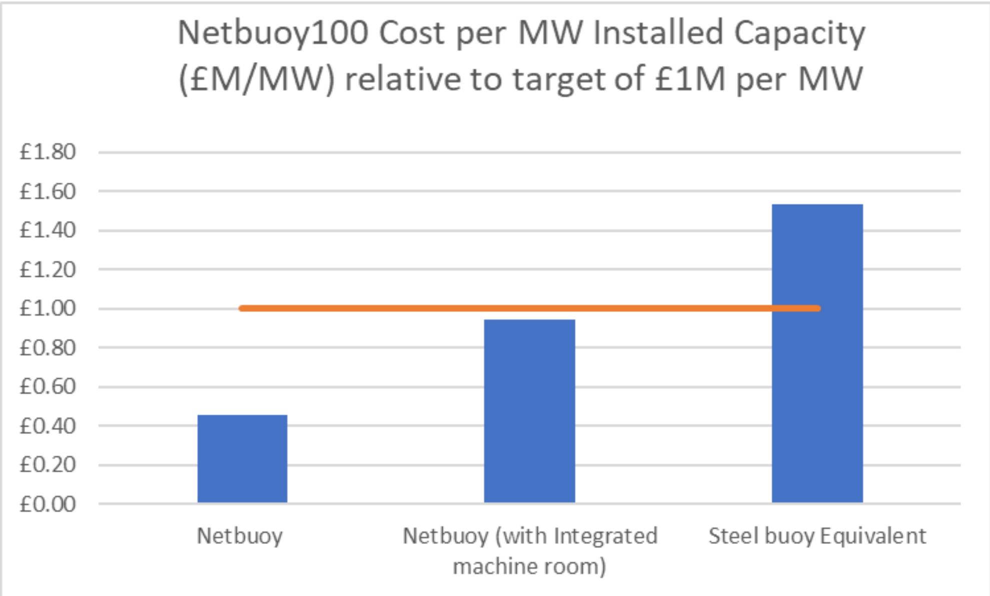
Stage 2 (recap)

The Stage 2 costing assessment of the NetBuoy100 was based on the Stage 2 FEED which provided a NetBuoy system specification that could be compared against the equivalent steel buoy. The equivalent steel buoy and the steel sub-systems of the NetBuoy (e.g., the machine room) had already been designed and costed as part of the Stage 1 FEED. The equivalent steel buoy has a mass of approximately 40 tonnes. This value is regarded as having high certainty as the structure has been designed according to DNVGL ship design rules, in concord with Black and Veatch, to achieve the required strength and rigidity. The NetBuoy costs were revisited following the completion of the Stage 2 FEED. High certainty costs were derived for the NetBuoy sub-systems. The costs of the net sub-system were based on a manufacturing assessment by TTI and current rope costs. Buoyant pod costs were based on up-to-date quotations from ship-to-quay fender manufacturers. Estimates were also supplied for the cost of ballasting and inflation systems unique to the NetBuoy and equivalent steel buoy. Transportation, installation, and O&M costs were based on a study by Quoceant for the deployment of a small array. The cost benefits between the NetBuoy and equivalent 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 £1million per MW installed capacity (refer to Figure 15).
- the largest portion of the cost saving of the NetBuoy comes from the reinforced elastomeric material

Figure 15: CAPEX for prime mover comparing NetBuoy configurations with an equivalent steel buoy (assuming steel buoy has integrated machine room)



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

- availability figures can be increased by 5%-10%, largely due to the ability to install the NetBuoy in higher limited sea states,
- extending the design life of the NetBuoy to 20 years produces significant annual O&M savings. This is considered wholly realistic with low probability of failure.

The CAPEX and OPEX cost benefit translated to significant improvements in levelised cost of energy (LCOE). LCOE was estimated using the 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 (e.g., the anchor, mooring tether and PTO), although relative costs have been adjusted to reflect improved transportation and installation costs and improved availability.

The LCOE comparison of the NetBuoy system and an equivalent steel buoy system has only considered the with integrated machine room scenario [14]:

- the NetBuoy LCOE is estimated to be £155 per MWh compared to £227 per MWh for the equivalent steel buoy system.
- If projected mass installation learnings rates are enabled, then the LCOE for the NetBuoy system reduces to the target of £150 per MWh.

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

Stage 3 update

The objective of the Stage 3 cost assessment was to use the latest design principles, which are embedded with the online NetBuoy design tool, to update the conservative cost basis for NetBuoy100 developed in Stage 2 and compare against the Stage 2 baseline.

The Stage 3 assessment demonstrated that the verified design principles significantly improved the conservative NetBuoy100 prime mover CAPEX (estimated in Stage 2 based on COTS fender quotations), resulting in a further potential CAPEX saving of 38% (£283 per kW in Stage 3 versus £455 per kW in Stage 2). This is achieved by using lighter reinforced membrane while retaining adequate design factors. The Stage 2 costs are deemed conservative when compared with the Stage 3 results for an equivalent volume buoyant pod with same draft/height ratio. The Stage 3 costs adopt the reasonable assumption the buoyant pod with lighter reinforced membranes could be manufactured using existing production tooling for marine fenders. Market demand may also drive standardisation of buoyant pod shapes and sizes depending on future WEC developer requirements (refer to section 1.6).

The OPEX costs estimates from Stage 2, based on the deployment of a small array of NetBuoy100 systems, are still considered valid. The experience of deploying a single scaled prototype has demonstrated it to be very manageable using a Multicat vessel. Furthermore, the extended soak tests and the fatigue tests of Stage 3 indicate that a NetBuoy prime mover will not require a significant number of maintenance interventions and is projected to have an adequate design life.

For consistency with Stage 2, the LCOE was estimated for the integrated machine room case. For a like-for-like comparison with Stage 2, the optimised design case in Stage 3 leads to a more modest additional

[14] The 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.

improvement in the LCOE for NetBuoy100 of 6%, but this is very much dependent on the underlying assumptions for other cost centres adopted within the WES LCOE tool.

1.6 Applicability to WEC Device Types

Demonstrating applicability of the NetBuoy prime mover to multiple WEC types has been a key aspect throughout the NetBuoy project. 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 system. The overall objective was to assess whether a NetBuoy system could replace large hulls in either steel or concrete.

In Stage 3 this applicability was further quantified and demonstrated by developing an online Design Tool which could be used by WEC developers to assess the suitability of the NetBuoy system for integration into their WEC architecture and provide an initial estimate of manufactured cost. The Design Tool can be accessed via https://www.netbuoy.co.uk/design-tool.

This work was further supported by tanks test which were used for verification purposes and demonstrate potential.

Figure 16 shows the various Design Tool NetBuoy configurations which can be adopted for WECs and the corresponding 6th scale models that were tested in the Kelvin Hydrodynamics Laboratory, Glasgow. Figure 17 shows the applicability of each configuration to various WEC types.

Figure 16 Design Tool configurations & corresponding 6th scale tank models

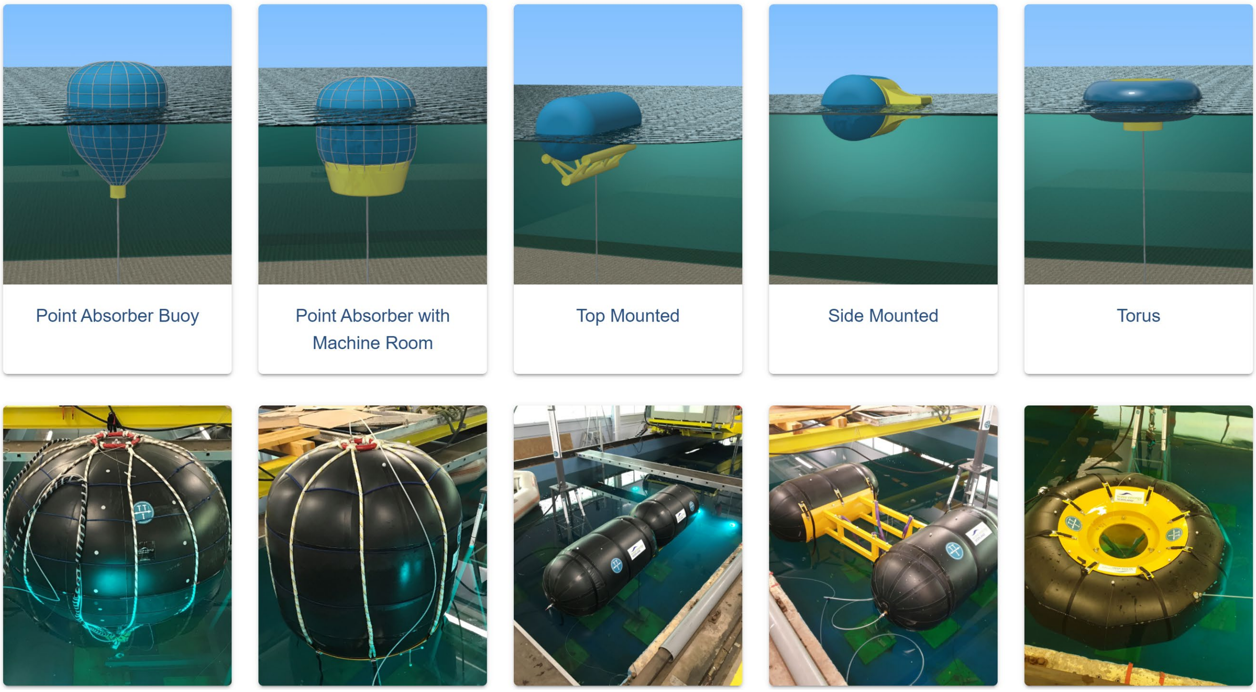


Figure 17 Applicability of NetBuoy configuration to WEC type

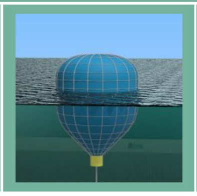
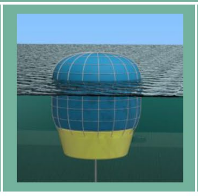
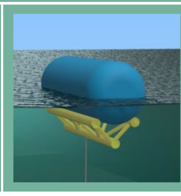
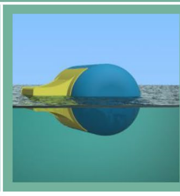
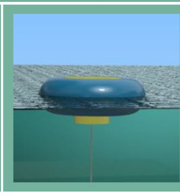
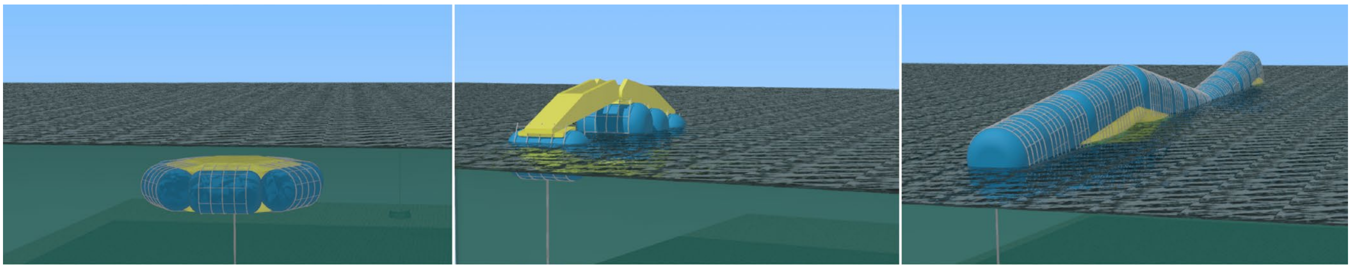
WEC Type					
Point Absorber	✓	✓			✓
Attenuator			✓	✓	
Hinged Raft			✓	✓	
Terminator			✓	✓	

Figure 18 Examples of NetBuoy technology being applied to different WEC architectures



1.7 *Features & Benefits*

Stage 3 has verified and demonstrated several key features and benefits of the NetBuoy system (Table 1).

Table 1

Functionality	The separation of key functions precludes the requirement to design for excessive load transmission through the inflatable elastomeric material.
Maturity	The two proven subsystems have high technological and commercial readiness and are widely used in other marine sectors.
Durability	Compliant & load shedding. Proven materials with high survivability and fatigue resistance. Principal materials do not corrode.
Manufacturability	Easily assembled with no heavy lifts. Vulcanised marine tenders are readily available off the shelf in high volumes at a range of sizes. Tension Technology International's established net manufacturing capacity can be upscaled or outsourced as required.
Affordability	Structural design assessment has demonstrated that NetBuoy™ assembly is less than 1/3 of the cost of steel based equivalent prime mover. Transportation, installation, and operation costs are all reduced.
Transportability	Lightweight yet strong. The foldable nature of the uninflated buoy means that the transport dimensions, along with mass due to material density, are significantly reduced compared to steel equivalents. Multiple deflated units can be readily

	transported from factory to quayside.
Maintainability	The NetBuoy™ system can be installed and recovered with smaller vessels. Individual net lines can be replaced, and established repair services already exist for vulcanised fenders. Ease of recovery and replacement improves availability
Installability	Hook-up and pull-down loads can be reduced by adjusting buoy pressure. Suitable for deployment with smaller vessels.
Scalability	Range of commercially available off-the-shelf fender units (up to 6m diameter). Modularisation can be adopted for greater swept volumes. Larger volume buoys possible with re-tooling as demand grows.
Applicability	The NetBuoy™ technology has been demonstrated to have high applicability to a wide range of WEC architectures, in addition to other marine technologies and sectors.

1.8 Communications and Publicity Activity

The team at TTI has published a significant number of papers in the past. Future papers will be referenced at www.tensiontech.com/papers and this is something we will consider for NetBuoy now Stage 3 has been completed. To date, public dissemination has largely been via WES wave energy conferences. We look to build on this.

1.9 Recommendations for Further Work

The recommendations for further work are largely covered under the confidential exploitation plan developed under Stage 3 which includes a commercial and technical road map.

The WES *"Structural Materials and Manufacturing Processes"* programme has enabled TTI to develop the NetBuoy system to high technical and commercial readiness. Stage 3 largely mitigated the key residual technical risks, and the natural next step is to integrate this technology into a larger-scale grid-connected WEC. This is an avenue TTI is already pursuing with an established WEC developer, that has identified NetBuoy as directly applicable to their point absorber technology. However, Stage 3, also confirmed good applicability of NetBuoy to a range of WEC architectures and this opportunity to exploit the technology more widely will also be pursued. TTI is also working on several opportunities to exploit NetBuoy know-how in other sectors, such as offshore aquaculture. We are also involved in proposals to consider the full lifecycle analysis and sustainability of NetBuoy relative to prime movers manufactured from conventional materials.

1.10 Project Collaborators

This project has been made possible thanks to collaboration and engagement of the following key subcontractors, suppliers, and project supporters. Figure 19 details the key project collaborators who have been involved during the three stages of the NetBuoy project. This project was made possible by the research and development contracts of the WES "Structural Materials and Manufacturing Processes" programme. WES has provided valuable technical feedback throughout all stages.

Figure 19 Project Collaborators (Stage 1 to Stage 3)

1.11 Useful References and Additional Data

TTI's dedicated website www.netbuoy.co.uk will be used to promote the NetBuoy system in the future.

2 Publicity Material

Filename	Media Type	Description
WESAC19 poster NetBuoyII TTI rev3	pdf	Poster for WES conference 2019
1500hrs_TTI_Yeats_NetBuoy_SMMP Rev1.pdf	PowerPoint	Presentation for WES conference 2019
www.netbuoy.co.uk	Website	Website for the NetBuoy technology