Project Neptune

WES PTO Stage 3 Non-Confidential Report

University of Edinburgh

Wave Energy Scotland, An Lòchran, 10 Inverness Campus, Inverness, IV2 5NA, Scotland
E: wes@hient.co.uk W: www.waveenergyscotland.co.uk

HIE
Highlands and Islands Enterprise
Iomairt na Gàidhealtachd 's nan Eilean

1 Project Outputs

1.1 Project Introduction

Technology Idea

C-GEN is a direct drive permanent magnet generator technology with so-called air-cored windings. The technology has been demonstrated at various scales:

- 20kW rotary machine proof of concept.
- 15kW rotary machine successfully installed and operated on a wind turbine.
- 6kW rotary machine successfully installed and operated on a wind turbine.
- 25kW axial flux multi-stage rotary machine as proof of concept of multi-stage topology pre scale up to 1MW.
- 1MW axial flux multi-stage rotary machine, demonstrator of a slice of a 6MW direct drive generator.
- 50kW linear machine for wave energy applications.
- 16kW rotary machine for vertical axis wind turbines – 4 machines built.
- [This project] 37.5kW linear machine for wave energy – 2 generators and 2 motors were built for Project Neptune.
- [Using learning from this project] 10kW rotary machine for wave energy – 2 machines have been built for Mocean Wave Energy Ltd.

For small wind applications the technology is at TRL 5, as it has been demonstrated in the real environment, but at multi-MW scale it is at TRL 4. For marine energy it is now at TRL 4 after Project Neptune. After successful completion of the deployment of the Mocean Energy device in the Novel WEC programme (WES NWEC Stage 3), C-GEN will be at TRL 5.

This project aimed to industrialise the manufacturing process of C-GEN; to take learning from Stage 2 on component marinisation in order to produce a generator for fully flooded operation; and to demonstrate O&M procedures in a non-factory environment.

Project Team

The project team consisted of 8 main partners: University of Edinburgh, Strathclyde University, Fountain Design Ltd, Quartz Elec Ltd., Severn Drives Energy Ltd., Carnegie Wave Energy Ltd., Laminaria BV, and Supply Design Ltd.

It should be noted that Quartz Elec Ltd. replaced Hayward Tyler Ltd. at month 12 of this project. Hayward Tyler withdrew from the project after 9 months, and it took 2 months to secure Quartz Elec as a direct replacement.

A summary of the team partners is provided below:

Univeristy of Edinburgh team:

Prof Markus Mueller (MM) has over 20 years of research and project management experience in the area of electrical machines for renewable energy converters. In the last 10 years he has managed £5m worth of research projects and supervised 15 Research Fellows and PhD students. Funding has come from EPSRC, EU FP6 & FP7, ERDF, Scottish Government, Scottish Enterprise and The Carbon Trust. In addition to undertaking blue-skies research, he has also commercialised research resulting in the spin out NGenTec. Expertise that he brings to this project includes integrated design of linear permanent magnet generators and research project management. Prof Mueller was employed on the project for 10% of his time.

Dr. Jonathan Shek (JS) is a Chancellor's Fellow at Edinburgh working on the control of electrical machines and drivetrained. In Project Neptune he provided support on sensors and DAQ.

Dr. Joe Burchell (JB) has a PhD in structural design of direct drive generators for wind turbines. He has an MEng degree in Mechanical Engineering, with expertise in engineering design. He will be responsible for the working on bearings, prototype design, commissioning and suppoting test. He also took on the role of site manager at Leith Docks, taking responsibility for drawing up H&S procedures for all operations in conjunction with Matt Tasker, as well as liaising with sub-contractors Forth Ports and Hunter Cranes. JB was employed for 24 months at 100%.

Dr. Ignacio Barajas Solano (IBS) has a PhD in electrical power engineering, and worked on electromagnetic bearings for linear generators for wave energy. In the project he took on the role of designing, building and installing the sensor array and data acquisitoin system. He worked with SDE and QE to commission the test rig, and then took on the role of Test Engineer, being responsible for all testing at Leith Docks. IBS was employed for 24 months at 100%.

Dr. Nisaar Ahmed (NA) has a PhD in CFD modelling of electrical machines. Nisaar was employed part time on the project to expertise in thermal modelling.

Matt Tasker – H&S Officer for School of Engineering. As well as being H&S officer, Matt has many years of CDM experience working in industry on site. Matt supported the UoE team in the drawing up of H&S procedures and RAMs for all lifting operations undertaken by Hunter Cranes.

Simon Robertson (SR) – is a member of the Policy and Innovation Group within the Institute for Energy Systems. He worked part time and was responsible for costing analysis and commercialisation, in particular deliverables, D18, D19, D21, D22.

Strathclyde team:

Dr. Alasdair McDonald: Dr Alasdair McDonald is a lecturer at the Wind Energy Systems Doctoral Training Centre based in the Institute for Energy and Environment, Department of Electronic & Electrical Engineering, University of Strathclyde. His research interests are centred on electrical generators and their application to renewable energy, especially wind turbine drivetrains. He studied Electrical and Mechanical Engineering at the University of Durham in 2004 and completed a PhD at the Institute of Energy Systems at the School of Engineering & Electronics at the University of Edinburgh in 2008. Subsequently Alasdair worked as a postdoctoral researcher in Edinburgh on a number of projects on direct-drive generators for wind and marine energy. In 2009, he co-founded the spin-out company NGenTec to commercialise their research of a novel air-cored generator for wind. Dr McDonald was Chief Engineer at the company in 2010-2012, during which time the company designed, built and tested a 1MW demonstrator. His expertise links directly into reliability and LCOE analysis, which he has gained from work on offshore wind.

Quartz Elec Ltd – is a machine refurb and servicing company based in Rugby, with experience of rebuilding all types of electrical machines for offshore and marine transport applications. QE was responsible for component manufacture, test rig fabricatoin and final assembly of the complete system. The main contacts were Mick Richmond and Tim Yeoman.

Fountain Design Ltd – FDL has worked with UoE for 15 years in the development of C-GEN technology, and I nparticular on manufacturing techniques. FDL took on the role of Project Manager and worked closely with QE providing support and training on component manufacturing techniques.

Severn Drives Energy Ltd – SDE is a supplier of medium voltage power converters for all types of applications within the energy sector. In this project SDE took on responsibility for designing, building and commissioning the power conversion system for the back to back linear motor generator test rig. The main contacts were Jonathon Jones and Nick Dutton.

Carnegie Wave Energy Ltd is an Australian wave energy developer of the CETO device which is a INSERT DEVICE TYPE– CWE worked with the UoE team on design case studies of C-GEN for the CWE devices. CWE provide technical and cost data for the study.

Laminaria is a Belgian wave energy developer of the LamWec device, which is a point absorber. Laminaria worked with the UoE team on design case studies of C-GEN for LamWec. The company provided technical and cost data for the study.

Supply Design Ltd is a power converter specialist company that has developed a module power converter solution. SDL worked with UoE to investigate module power electronics for C-GEN.

Project Success

The main measures used to determine project success are listed below, which have been achieved to a degree that the outcomes provide the evidence required to design and build C-GEN technology for fully flooded operation with confidence:

1. Design, build, and commission the Project Neptune Test Platform.
2. Achieve the target outcomes specified according to Affordability, Performance, Availability, Manufacturability, Installability and Survivability.
3. Fully flooded operation of the C-GEN technology in the marine environment.
4. Demonstration of O&M procedures in a non-factory environment.
5. Design Case Study reports for two developers: Carnegie and Laminaria.
6. Technology and Commercial Roadmap, with a plan for a Stage 4 application.

1.2 Description of Project Technology

[Describe the key features of the project technology, and its anticipated advantages.]

C-GEN is an innovative multi-stage air-cored PMG technology that is applicable to direct drive, slow or medium speed generator designs. The differentiating design features of the patented C-GEN design include:

- an axial flux topology with C-shaped rotor core
- an air-cored stator arrangement
- generator divided into several axial generator stages that are electrically independent
- generator rotor and stator divided into low weight standardised modules around the circumference

The C-Gen PMG consists of lightweight stator and rotor modules. The low generator and module weight of the NGenTec technology reduces O&M costs compared to traditional ironcored, radial flux PMG systems. The maintenance of drive train components, if necessary, can be carried out with lighter lifting equipment or an internal turbine crane. Multiple generators consisting of simple, lightweight modules can be "stacked" back-to-back along the shaft of a wind turbine to create a multi-MW rating without increasing the machine diameter. This means that for certain generating system line failures, one generator line can be isolated, enabling the wind turbine to continue generating revenue whilst maintenance is scheduled. This redundancy characteristic is even more relevant for remote areas with challenging conditions for access, e.g. offshore wind farms. In the C-Gen PMG the number of generators in operation can be adjusted based on wind conditions to optimise the power output, efficiency and increase longevity. In conventional PMGs magnets try to align themselves with steel teeth onto the stationary part of the generator and cogging torque will result in overcoming this alignment force. This characteristic increases the cut-in wind speed (the minimum wind speed at which the turbine produces power) and creates vibrations in the generator. C-Gen does not have any cogging torque to overcome (there is zero cogging torque as there is no iron in the stator), and can thus generate power at low wind speeds and do not create vibrations in the generator, which can also reduce noise.

The C-Gen generator technology therefore has the following USPs over existing generator technologies used for direct drive:

1. No Magnetic Attraction Forces closing the airgap - this simplifies the support structure required, and makes assembly of the stator and rotor modules easier.

2. No cogging torque - more of the input mechanical energy will be converted to electrical energy, and noise and vibration will be reduced.

3. High Degree of Modularity - the use of air-cored coils allows a high degree of modularity in both the stator and rotor construction.

4. Higher availability - Due to the high degree of modularity the C-Gen generator is a multi-stage machine, which means that it is built up of a number of machines, eg a 4 stage 1MW generator consists of 4 separate 250kW machines, all of which can be isolated. Hence if there is a fault in one stage, then it can be isolated and the remaining 3 stages can generate. In a conventional generator a fault in a machine will result in complete shut down, and hence no revenue is generated. BY being able to operate with few stages the C-Gen generator will have more availability, increasing annual energy yield and hence reducing LCOE.

5. Ease of O&M - the high degree of modularity enables replacement of single faulty modules rather than the complete machine. This reduces O&M costs and increases the turnaround of any O&M procedures. Depending upon the size of the device, the O&M procedure could be done on board a ship using an on-board crane. Modules can be designed to have a mass typical of craneage on a ship.

1.3 Scope of Work

[Outline the work undertaken during this project, and the reasoning for the key activities.]

The C-GEN technology has been proved at various scales, mainly for wind energy, and there is a good understanding of design for that application. A 50kW linear machine was demonstrated as part of the Carbon Trust Marine Accelerator program, which highlighted performance issues with certain components: thermal performance of the windings and the bearing design. Both these components account for high failures in wind energy systems, and it can be assumed that the situation will be similar in wave energy. The 50kW demonstrators was tested in a lab environment, rather than an application relevant environment. Hence the focus of the project was on understanding the performance of windings and bearings when the generator is operated in a more realistic environment, and in this case it was decided to run the generator fully flooded. The project WPs were designed around this rationale and are summarised below:

WP1 – Project Management, Lead FDL - to manage all partners in the project effectively to successfully deliver all the project outcomes within time and budget, whilst mitigating known and unknown risks as and when they occur.

WP2 – Engineering Design, Lead UoE - to finalise and obtain certification of the integrated electro-mechanical design of the Stage 3 demonstrator, providing full CAD drawings signed off for component manufacture. WP2 included all aspects of the complete system design: electrical; mechanical structural analysis; power converter system design; sensor array and data acquisition; and test rig structural design. The engineering design was assessed by DNVGL.

WP3 – Operation and Maintenance Analysis, Lead Stathclyde University - provide experimental data and develop processes to support the targets for reliability, availability, maintainability and OPEX. The WP is divided into tasks covering: the development of O&M procedures for C-GEN to be demonstrated during the testing phase; predictive maintenance strategies; assessment of component reliability.

WP4 – Generator Component Manufacture and Assembly, lead Quartz Elec - to manufacture all components and machine modules based on the design from WP2 in compliance with DNVGL recommendations, to ensure quality and final certification of the manufacturing process. The WP was divided into tasks including: manufacture of tooling; stator and PM translator module manufacture for the motor and generator; stator component tests; fabrication and assembly of test platform; assembly of motor and generator modules onto the test platform; build of the power conversion system; and assessment of the manufacturing process by DNVGL.

WP5 - Sensor Array, Control & Condition Monitoring, lead UoE - to implement a sensor-based condition monitoring and control system on the Stage 3 C-GEN. The WP included tasks on the design of the sensor array and the data acquisition system; and modelling of the complete test rig to investigate system control.

WP6 – Marine Installation, lead UoE - to liaise with Forth Ports and to prepare the infrastructure and sub-contractors for wet testing in the dock. Leith Docks was chosen to be the test facility. Site preparation was required to make the site suitable for the test programme. A container/trailer was used for the power conversion equipment, and also provided workspace for the test engineers. Power was provided by a diesel genset. A portable toilet was installed on site, and catering facilities were close by. Health and Safety procedures were drawn up for all operations in and out of the dock. RAMs for lifting operations were drawn up in conjunction with the crane subcontractor, Hunter Cranes.

WP7 – C-GEN Demonstrator Test Programme and Design Verification, lead UoE, to test the Stage 3 C-GEN demonstrator in a real environment taking into account typical load profiles, fault conditions, and to use results for design verification and demonstration of the main USPs of the C-GEN technology. A test programme was drawn up for component tests pre-assembly; system functional tests during and after assembly in the factory; dry tests and Leith Docks; and wet tests in the dock at Leith Docks. The final wet test programme was assessed by DNVGL before wet testing commenced. Functional tests were undertaken at the factory to check system control and correct operation of the power converter system. Standard machine tests were undertaken: no load at different velocities; full and part load tests; heat run to check thermal performance. O&M procedures were also demonstrated: a stator module was removed and replaced and two bearing modules were removed and replaced. These procedures were completed in situ on the dock side, not in a factory environment.

WP8 – Engineering Design Tool Refinement, **lead UoE**- to make the existing design tools more industrialised by including manufacturing aspects, and including any changes as a result of the 3rd party recommendations and experimental testing. The design tool will be refined depending upon the correlation with experimental results, in order to increase confidence in the design tool. System models have been developed to allow simulation of the generator and power conversion system, the output from which will feed into power converter and control design. Module dimensions are then output to Solidworks to allow module CAD drawings.

WP9 – Future Developments, lead UoE - to investigate new technologies that could enhance the performance and reliability of C-GEN and expand the number of devices to which C-GEN could be applied. Two different aspects were investigated: Modular Power Converters and Velocity Enhancement Techniques. The WP was therefore divided into two:

WP9.1 Modularised Power Converter, Supply Design Ltd–a single VSI converter is being used in this project, but this solution does not take advantage of the modular nature of C-GEN. In this task Supply Design investigated the feasibility of a modular power converter solution integrated with each statorwinding module. Simulation studies to show how a modular system will operate with C-GEN were undertaken, with modules connected in series and parallel groups. The main outcome of this task will be design guidelines and recommendations for modular converters within C-GEN.

WP9.2 Velocity Enhancement Techniques, UoE –the Carnegie design case study in WES Stage 2 highlighted the challenges of direct drive, in that the low peak velocity of the Carnegie device led to an efficiency in the low 70s. Ben McGilton, a PhD student at UoE, funded by the CDT in Wind and Marine, worked on magnetic gearing systems for wave energy devices. His results were fed into Project Neptune to investigate how C-GEN could be integrated with magnetic gear systems in both linear and rotary form.

WP10 Design Case Studies and LCOE Analysis, lead UoE - To complete industrial designs of C-GEN with power conversion and LCOE analysis for the device partners, Carnegie and Laminaria. The study built upon the case studies undertaken in the WES Stage 2 project. More optimised designs were produced using detailed design and operational data from the developers. CAD drawings showing how C-GEN interfaces with the wave device have been produced. For Carnegie both rotary and linear generators have been designed, whereas for Laminaria only a rotary solution was designed as a direct replacement for their current PTO. As well as modelling single devices the study included designs for a small 10MW array and a large 100MW array. Annual energy output was calculated for the designs at a number of European sites, in order to compare LCOE. In all costing studies C-GEN was compared with the developer's existing PTO system.

WP11 Commercialisation, Market and Economic Strategy, **lead UoE** - in this WP information from the other work packages was collected and analysed to investigate the economic and life-cycle assessment of the C-GEN generator technology. Competitor analysis was undertaken to highlight the unique selling points of the C-GEN technology, but also to highlight any gaps. Recommendations for de-risking and reducing the uncertainties on the development of the C-GEN generator technology were made in order to satisfy device developer needs. Market analysis was undertaken to identify potential commercial opportunities for C-GEN within and outwith the marine renewable sector. A FEED study was completed for a commercial project with Mocean Energy Ltd., the design from which has actually been realised and will be demonstrated in Mocean's device in summer 2020. Short- and long-term recommendations were made for the commercialisation of C-GEN.

WP12 C-Gen Technology Optimisation, lead UoE, with sub-contractor DNVGL - this WP cuts across all WPs with the objective being to optimise the processes involved in industrialising, commercialising and certifying C-GEN technology for marine and wider sectors. The methodology in this WP followed elements of DNVGL's certification process outlined in DNV-OSS-312 Certification of Tidal and Wave Energy Converters further detailed in DNVGL SE-0120 (DRAFT), specifically section 2.3 "Certification scope for prototype, type and project certification", but adapting it to PTOs in WES Stage 3. Technology Assessment and FMECA studies were completed by UoE. Test programme documentation was assessed by DNVGL, and DNVGL attended the test site to witness testing. DNVGL will provide statements of assessment for the technology, test programme, design and manufacturing process. Recommendations made by DNVGL will feed into the future development of C-GEN, and will also provide independent assessment of the technology.

1.4 Project Achievements

[What went well? Project would have been even better if…?]

The main project achievements can be summarised as follows:

1. Demonstration of a Fully Flooded C-GEN Linear Generator – this achievement fulfils the main objective of Project Neptune. The generator was operated under no-load, part load, full load and overload conditions, demonstrating excellent thermal performance, with the temperature rise above ambient no more than 10 °C. The generator operated with faulty modules, demonstrating the fault tolerant aspect of the technology. By operating fully flooded expensive seals are not required, providing the potential for reducing CAPEX and OPEX. The bearing solution was custom designed for fully flooded operation and ease of O&M, providing a cost effective and robust solution, that could be used in other marine energy technologies. Marine material coatings

were used, and provide adequate protection for the operating period, but more work is required. Project Neptune provided further validation for the component testing undertaken in the WES Stage 2 project. Demonstration of C-GEN in a fully flooded environment brings C-GEN up to TRL 5-6.

2. Design, Build and Test a Linear Motor-Generator Test Rig – in order to test the C-GEN generator a method of driving the machine was required. A number of mechanical options were considered, including hydraulics, nodding donkey, and a drum and cable arrangement. Some were either too expensive or did not provide the functionality required to test the linear generator. The final solution was a back-to-back linear motor-generator test bed rated at 75 kW. The resulting design shown in Figure 1, occupies a 3mx3m footprint, and is 7m in height. The linear motor has a peak speed of 1m/s, at a stroke of 3m. As far as the project team is aware it is the biggest linear machine test rig in the UK, if not Europe. With the power conversion drive system it is controllable in terms of displacement and load profile. The test rig can be operated in both dry and wet conditions.

3. Manage a marine test site – Testing the PTO in a marine environment was one of the key objectives of the Stage 3 PTO funding call. Before Project Neptune, the team at Edinburgh had no such experience. During the project the team had significantly upskilled on CDM Regulations, crane operations, preparation of RAMs, and H&S procedures for operating in a dock environment. Project Neptune had excellent support from the School of Engineering Health and Safety Office, Matt Tasker, who has many years of CDM experience. The new skills gained enhance the career opportunities for team members, but also enable the Edinburgh team to confidently bid for further work involving operation in the marine environment.

4. Demonstrate O&M procedures in a marine environment – one of the main USPs claimed for C-GEN is the ease of O&M procedures due to the high degree of modularity within the technology. The modular aspect allows the generator to continue operating with faulty modules, and the replacement of faulty modules can be done on site, not in a factory environment as would be the case for conventional machines. During the test phase module and bearing pad replacement were both successfully demonstrated on the dock side. The generator was removed from the dock onto the side, where a stator module was removed, positioned on the ground, and then re-inserted into the machine, using standard craneage. The module replacement procedure took 40 minutes, and this was the first time that it had been attempted. With better connectors between the stator modules the time could be easily reduced. Bearing modules were removed and replaced by hand, taking less than 2 minutes. With the right kind of craneage on board a ship, such procedures could be completed on board a maintenance vessel. The impact of the modular design on easing O&M procedures will result in reduced OPEX and increasing availability, thus leading to lower levelised cost of energy.

5. Industrialising the Manufacturing Process – the manufacturing techniques employed in previous prototype demonstrators were used within Project Neptune, namely cast PM translator modules, and stator modules potted in epoxy. In previous projects machines were built by a specialist prototype developer, Fountain Design Ltd, but in Project Neptune two industrial partners were brought into the team – Quartz Elec Ltd., a large electrical machine manufacturer, and Severn Drives and Energy Ltd., a supplier of medium speed electrical drives. Quartz Elec Ltd. provided industrial scale coil winding facilities enabling high volume manufacture for the manufacture of stator modules, and in-house industrial design and manufacturing standards for the design and build of the complete Project Neptune test rig. The PM translator modules were manufactured by a foundry in E Kilbride to a higher quality than previous modules and according to casting standards, Severn Drives Energy designed, built and commissioned the power conversion system for the complete test rig, bringing their own in-house industrial best practice and standards to the project. The overall engineering design and manufacturing

process has benefited from industrial input leading to more industrialised manufacturing procedures, which will impact positively on quality and cost.

7. Forming industrial partnerships for future development – within the project there were 6 industrial partners:

- Quartz Elec Ltd., Severn Drives Energy, and Fountain Design Ltd – engineering design and manufacturing.
- Carnegie Wave Energy and Laminaria – wave device developers
- Supply Design Ltd. - future technology partner.

With the manufacturing partners and the future technology partner we have developed a very good team enabling Edinburgh to develop C-GEN with more industrial capability and credibility. This has already had an impact in that Edinburgh supplied Mocean Energy with two C-GEN generators for the Stage 3 WES Novel Device Demonstrator, with Quartz Elec and Fountain Design manufacturing the generator according to Edinburgh's design and Supply design Ltd providing the power conversion system. Going forward, we want to formalise these partnerships regardless of the commercialisation pathway adopted by Edinburgh. With these industrial partners on board C-GEN technology will have greater industrial and commercial credibility.

Detailed design case studies were completed for Carnegie and Laminaria. With the manufacturers on board and with learning gained from Project Neptune, we will be able to work with wave device developers to provide accurately costed designs.

8. Mocean Energy Blue Horizon Project – Mocean Energy has been funded through the WES Stage 3 NWEC call to design, build and test a hinged device rated at 30 kW, referred to as Blue Horizon, with sea trials due to start in the summer of 2020. Mocean Energy selected the C-GEN technology for the power take off. Two generators have been designed, built and tested back-to-back by Supply Design Ltd. This project provides the first commercial sale of C-GEN to a wave energy developer, and with sea trials taking place it will take C-GEN to TRL 8-9.

Areas that did not go so well:

1. Site management at the start – The Edinburgh team had never managed such a project with testing in a marine environment, and thus lacked experience in CDM and preparation of RAMs associated with lifting and marine operations. However, once the newly appointed School of Engineering officer, Matt Tasker, became involved the team upskilled significantly. Clear roles with regards to site management and testing were allocated, and all operations thereafter ran very smoothly.

2. Losing Hayward Tyler Ltd. (HTL) at month 9 - At the start of the project the manufacturing partner was HTL, with whom we had built up a good relationship before the project. HTl's main product line is sub-sea pumps for offshore oil and gas, and thus provided the ideal company for a marine energy PTO. Before the project even started the main contact left HTL, and although a new contact was put in place, it became clear that the company was having financial problems. HTL was taken over by a much larger group with a diverse engineering portfolio, and decided that HTL should focus on more commercial projects, withdrawing from Project Neptune. Significant resource had been invested in HTL in terms of engineering and manufacturing design, with sample moulds procured for testing out injection moulding techniques. Very little of this learning was transferred into the project, as the new manufacturing partner had no injection moulding capability, but it will be used to stimulate future projects. It then took another 2-3 months to bring in a new partner, Quartz Elec, who provided

an excellent replacement. As with any new partner time was required to get up and running. The reduction in budget and change in skills set available meant that roles had to be redeployed amongst the team, mainly within Edinburgh, which also had knock on effects in terms of workload, in particular liaising with DNVGL.

3. Better engagement with DNVGL – one of the objectives of the projects was to obtain independent review of C-GEN technology, in particular the design, manufacture and test aspects of the project. At the start of the project the manufacturing partner was HTL, who took on the role of preparing the documentation for DNVGL. HTl's main product line is sub-sea pumps for offshore oil and gas, and so their procedures are aligned with independent certification bodies. However, when HTL withdrew at month 9, this capability was lost to the project. After 3 months Quartz Elec joined the project as manufacturer, but did not have the resources to take on the role of dealing with DNVGL. Edinburgh took on this role with existing staff taking responsibility, but the documentation and level of understanding of appropriate standards was underestimated. With the delay that had been incurred by losing HTL, and the additional demands on existing staff in meeting the other deliverables, the engagement with DNVGL was not as effective as it should have been. DNVGL have been engaged and provided review of procedures adopted, producing statements of assessment with recommendations, but not to the level originally planned. In future projects a person would be employed to work full-time on aligning the engineering design and manufacturing process to standards to enable certification. Such a role is highly specialised and requires 100% time.

4. Test Rig Performance – although the test rig has performed well there have been a number of issues, which have come to light as a result of the test programme. These can be linked to engineering design and manufacturing, but such issues are part of the normal process of learning within the RD&D environment.

Both the linear motor and generator have coils that can be either active or in-active depending upon the position of the translator. When coils are active they are overlapping with the magnets, and thus useful force and power is being produced. An in-active coil is not overlapping with magnets, but it is still connected within the circuit, and thus a voltage drop is across such a coil (about 20V peak), which introduces a loss. In the case of the motor there are 9 coils not overlapping at any one time, resulting in a significant voltage drop. The voltage being applied by the power converter is therefore being divided between the active and in-active coils, with not enough being used to produce force to drive the generator load demand. On the generator the non-overlapping coils results in reduced efficiency and force output, so that the generator is unable to produce full rated force at the specified current. This effect is related entirely to linear machines, and is not an issue in rotary machines. One can switch coils in and out using power electronics switches, but this adds to complexity, cost and will impact reliability. One solution is to have a short stator, so that the coils are always overlapping with magnets, but this will also add to cost.

During wet testing the linear motor and generator experienced a number of failures on the stator modules. Even with these failures the system continues to operate demonstrating the fault tolerance of C-GEN technology. However, such failures are not good for OPEX. At present the reason for failure is not known, but it is expected that there has been water ingress at the cable gland. Better sealing techniques are required to improve the reliability of the stator modules.

5. Manufacturing issues of epoxy supplier – with the original manufacturing partner HTL, the manufacture of the stator was to follow their existing injection moulding techniques. However, with a new partner coming on board halfway through the project we decided to revert back to the original stator manufacturing technique with coils potted in epoxy. The epoxy used in all previous prototypes was specified, and supplied to Quartz Elec, who implemented the existing proven potting process under the supervision of Fountain Design Ltd, who developed

the process. However, after numerous failures it became clear that the epoxy and hardener supplied had very different curing characteristics to those expected, even though the labelling was correct. After various trials and discussions with the supplier, the supplier admitted that the epoxy curing properties had changed, and issued the correct curing procedure. The manufacturing process was delayed by 2 months due to this supplier issue, which was essentially outside our control.

1.5 Applicability to WEC Device Types

[Describe which WEC device types this technology is compatible with, and identify which you think are the strongest potential partners for your PTO.]

C-GEN is compatible with a number of different device types as outlined below:

1. **Point Absorber** – linear generators are very well suited to point absorbers with SeaBased a very good example of using a linear generator. C-GEN is ideally suited to the point absorber device type, and the strongest partners are Mocean Energy, Carnegie Wave Power Ltd, and Laminaria. A design study has been completed for Carnegie and Laminaria, and two generators have been designed and built for Mocean's Blue Horizon device, which will undertake sea trials in summer 2020.

1. **Oscillating Wave Surge Converter** – a design study was completed for the Oyster device several years ago, with a rotary C-GEN. It was found that some form of single stage gearing was required in order to make the system economic, but the generator speed would still be very low – 15-20rpm. As part of Project Neptune we have also conducted a study to investigate the use of magnetic gears to increase velocity. A small-scale device has been built as part of a PhD, with tests in FloWave demonstrating the concept and showing promising results. At present no company has been identified.

2. **Oscillating Water Column** – High speed rotary generators are used in OWCs. Although C-GEN has been primarily designed for low speed applications thus far, it can be adapted for high speed. Similar electrical machine technology has been used in automotive and aerospace applications, where rotational speeds are similar to a generator in an OWC. The Stage 3 project has focussed on linear generators and hence no developer has been identified.

3. **Overtopping/terminator**- The permanent magnet generators proposed for overtopping devices such as Wavedragon are of the conventional PM generator topology operating at low to medium speeds. C-GEN can be designed for such an application and would be very compatible, but no partner has been identifed because there are no developers of this device at present.

4. **Submerged Pressure Differential** – The AWS is the most well-known device of this type, and it employed a direct drive linear iron cored permanent magnet generator. A design study for AWS using C-GEN was completed several years ago, and it was found that C-GEN is compatible with this device type. There has been some contact with AWS and the project team had discussions with AWS regarding the PTO for their Stage 3 NWEC device.

5. **Rotating Mass** - One example of such a device developed by ECN, Searev, was to use a conventional iron-cored permanent magnet direct drive generator. C-GEN could be used as a direct replacement for the iron cored PM generator. The Stingray device being developed by Columbia Power Technology

produces rotary motion and currently uses a direct drive rotary PM generator. UoE has a relationship with CPT, and presents the strongest potential for partnership. Other devices of this type such as Wello's Penguin Wave device would also be of potential interest to C-GEN.

1.6 Summary of Performance against Target Outcome Metrics

[Describe, and quantify where appropriate, the technology performance against the target metrics of Affordability / Performance / Availability / Survivability]

Affordability –

- **Targets:** In previous work on C-GEN supported by the Carbon Trust Marine Accelerator the LCOE of C-GEN was £180/MWh, and CAPEX of the generator was calculated to be £850k/MW. In line with WES aspirations target outcomes for CAPEX are £400k/MW for a single device and £310k/MW for a 100 MW array.
- CAPEX
    - Stage 3 aim: £400k/MW – NOT ACHIEVED
    - 100MW Array: £310k/MW – NOT ACHIEVED
- **Outcomes –** the outcomes are based on design and costing studies of partner devices at different sites around Europe and the UK.
    - The CAPEX targets were not achieved, but the estimates from the device design and costing studies show CAPEX of the right order: for a 100 MW array of Carnegie devices C-GEN came out at £674k/MW, and for the Laminaria device C-GEN came out at £368k for a 260 kW rated device. With more industrialisation and economies of scale these costs will come down. Compared to the devices existing PTOs C-GEN was competitive, lower in one case, but higher in the other. With respect to other types of PTO, C-GEN showed the lowest CAPEX.
    - A study of LCOE for the two devices at different sites produced an LCOE for C-GEN in a 100 MW array ranging from £90/MWh to £200/MWh, which is in the right ball park with respect to WES' target of £150/MWh**.**
    - More work on developing accurate CAPEX and OPEX cost models taking into account C-GEN's modular nature is required to develop confidence in costings.

Performance and Scalability – can be divided into two: Rated Capacity and Power Conversion Efficiency

- **Rated Unit Capacity**
    - High degree of modularity – ACHIEVED – C-GEN is a highly modular machine.
    - Typical module rating 25 – 50 kW – the module was 12.5 kW for this machine, but there were two generators making up the total rating of 75 kW. From experimental tests, however, the maximum module power achieved was in the region of 5 kW due to technical issues described earlier.

- **Power Conversion Efficiency**
  - Target: Low velocity, 0.5 – 0.6 m/s : 70 – 75%; Velocity up to 2 m/s : 80 – 90%
  - Efficiency data is currently not available from experimental results, but because of the losses in in-active coils these targets are not expected to be achieved. Further system modelling showed efficiency nearer 50% due to losses in inactive coils.
  - Initial results from the Mocean Energy tests, show that the drivetrain efficiency is 85-90% efficient, which includes both the gearbox and low speed C-GEN generator. It is expected that the C-GEN generator will have an efficiency in excess of 90%, satisfying the target. A rotary C-GEN machine is used in the Mocean device, and so there are no in-active coils.

Availability

- 100MW Array Target
  - Mean Time Before Failure – 5 years
  - Mean time to repair – 2 days (summer), 25 days winter
  - Availability – 97 - 98%
  - Module repair and replacement on board ship.
  - Stage 3 module replacement – 2 hours on dock side – **ACHIEVED**

- **Achievement**
  - Without operational experience over years it is difficult to confirm MTBF, MTTR and availability targets, but evidence can be provided to support these aspirations.
  - Successful operation of a fully flooded C-GEN proves the thermal performance so that the insulation lifetime is not affected, but a number of stator blade failures during flooded operation requires further work to support availability claims.
  - During the project in-situ O&M procedures were successfully demonstrated, in particular stator module replacement and bearing pad replacement, both of which were achieved in less than an hour. This ability to replace modules quickly and easily does support MTTR and Availability targets, but more work is required to better quantify the benefit.
  - Stator winding module failures were observed during the wet tests, but the generator was able to continue generating at part load even with faulty modules, thus contributing positively to availability.

Survivability

- **Electrical survivability**
    - 5 times rated current under fault conditions.
    - Thermal results in stage 2 support target.
    - Thermal results in Stage 3 provide additional support to target. Winding temperatures did not exceed 20 °C, so that significant overload could be tolerated without complete machine failure occurring.
    - Stator winding module failures were observed during the wet tests, but the generator was able to continue generating at part load even with faulty modules, thus contributing positively to survivability.
- **Mechanical survivability**
    - 5 times rated force/torque
    - Accelerated tests performed by NGenTec in a previous project support target.

1.7 Communications and Publicity Activity

[Describe any public promotion of this technology, such as academic papers and posters, press releases, news coverage etc.]

Papers 1 & 2 have been presented at international conferences, and papers 3 & 4 have been submitted to conferences, still awaiting acceptance.

1. *The Design and Build of a 75 kW Linear C-Gen Generator Prototype for Wave Energy Power Conversion*, Joseph Burchell, Ignacio Barajas-Solano, Mike Galbraith, Nisaar Ahmed, Okechukwu Ubani, and Markus Mueller. European Wave and Tidal Energy Conference, Naples 2019
2. *C-Gen Neptune, A Direct Drive Generator For Offshore Renewable Energy Converters*, Mueller, Burchell, Barajas Solano, Galbraith, presented at the Conference on Offshore Renewable Energy, Glasgow Sept 2019.
3. *Operation of a flooded linear generator within the marine environment,* Burchell, Barajas Solano and Mueller, submitted to IET Renewable Power Generation Conference, Cork Sept 2020.
4. All Energy, May 2020 – abstract submitted: C-GEN – a direct drive generator technology for marine renewables.

1.8 Recommendations for Further Work

[Describe the key areas of activity required to further develop this technology towards commercial deployment.]

Based on the technology learning experience within Project Neptune, outlined elsewhere in this document the following recommendations have been made for further work:

1. Improved Marinisation – although the stator blades were tested in water as part of the manufacturing process a number of blade failures have occurred during the wet testing phase. Inspection is taking place to understand the root cause of the failure, but it is clear that further work is required for reliable marine operation.

2. System Control & Power Conversion – The test results highlighted issues with respect to overall system control. Further work is required to develop techniques and designs to switch out in-active coils in linear machines, without incurring added complexity to the power conversion system. Power electronic converters on each stator module could be used to switch modules in which there are in-active coils. C-GEN stator power converter modules were investigated in Project Neptune as part of *Future Developments for C-GEN*, and further investigation is ongoing through a PhD studentship at University of Edinburgh. At present a sensor is used to control the output from the generator, and although it worked well in the project, tests were conducted in a controlled marine environment. Sensorless operation would provide a more robust and reliable solution.

3. Magnetic gearing systems for rotary C-GEN – Wave devices operate with low velocity high force, the opposite of what is favourable for electrical machines. Magnetic gearing systems offer a robust and reliable solution for C-GEN in very low speed applications. Such systems were investigated in Project Neptune as part *Future Developments for C-GEN,* and further work is being undertaken with Mocean as part of an EU funded Marine Energy Alliance project. As well as direct drive systems, an integrated C-GEN magnetic gear generation system would provide another drivetrain option for marine renewables enabling scalability.

4. Industrialisation in the stator module manufacture – In Project Neptune existing stator module manufacturing techniques were used due to a change in manufacturing partner. Although this technique is well proven it is very labour intensive, and hence costly. For volume manufacture more automated methods are required, such as injection moulding. It is therefore recommended that alternative manufacturing techniques be investigated, and this should be a priority.

5. Costing model - As stated in the section on Targets, Project Neptune did not achieve the Affordability targets for CAPEX, but initial costings show that C-GEN is competitive with existing PTO solutions. At present all designs are customised according to the application in question, which makes it more challenging to deal with generic enquiries. In order to deal with customer enquiries, it is recommended that a more accurate costing model is produced for a range of machines in wave and tidal, so that we can attract potential customers to move to the design phase.

1.9 Useful References and Additional Data

[Provide references to any additional reports, data, websites or other information that support the content of this report. State clearly whether the referenced material is confidential or publicly available.]

References:

1. http://carnegiewave.com/ (last accessed 20th December 2016)
2. http://albatern.co.uk/ (last accessed 20th December 2016)
3. http://www.laminaria.be/ (last accessed 20th December 2016)

2 Publicity Material

[Please supply WES with any logos, images and video files that are non-confidential and available for WES to use to promote WES supported projects. Use the table below to provide filenames and descriptions for all such material]

Filename	Media Type	Description