C-GEN Direct Drive PTO

WES Power Take Off
Stage 2 Project
Public Report

University of Edinburgh

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

Technology Idea

C-Gis 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.

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 and for marine energy at TRL 3.

This project aimed to address design challenges at a component level when considering the marine environment, and thus on successful completion of the project the technology would be at TRL 4, making it ready for the next stage of development in a Stage 3 WES project.

Project Team

The project team consisted of 3 main partners: University of Edinburgh, Strathclyde University and NGenTec Ltd., with Fountain Design Ltd as a sub-contractor.

About halfway through the project NGenTec Ltd decided that it could no longer support the project and were planning to go into administration. University of Edinburgh purchased the core IP from NGenTec Ltd. and thus ensured that the lead partner was in the best position to exploit this technology commercially beyond Stage 2 fulfilling its contractual requirements.

A summary of the original team is provided below:

UoE team:

Prof Markus Mueller 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 resaerch 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 will be employed on the project for 10% of his time.

Nisaar Ahmed has been a PhD student at UoE for the last 4 years working under the supervision of Prof Mueller. His PhD focussed on the thermal performance of electrical generators in OWC wave devices, and in particular modelling the airflow through the turbine and how it then interacts with the generator. Nisaar used CFD modelling and wind tunnel tests to verify his results. He is in the process of writing up. In addition he is working with an SME, Airborne Energy, to model a novel vertical axis wind turbine. Expertise that he brings to this project includes CFD modelling in general and CFD applied to electrical machines for renewable energy applications. Nisaar will be employed on the project as a Research Fellow for 12 months at 100% of his time, and is referred to as UoE1 in the application.

Joe Burchell is in the process of writing up his 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, build and test, and will liaise with the sub-contractor, Fountain Design Ltd. Joe will be employed on the project for 12 months at 100% of his time, and is referred to as UoE2.

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. He will spend 10% of his time on the project.

STRATH1 – Godwin Jimmy is currently working on the reliability and LCOE analysis of wind turbines incorporating direct drive generators for his PhD in the Wind CDT at Strahclyde. He took a year out from his studies to work 100% on WP6 & 7, and will contribute to WPs 8 & 9.

NGenTec – was one of the original partners, but withdrew halfway through the project as the company was planning to go into administration. UoE and Strath took on their WP9 responsibilities with respect to industrial engagement, the design case studies and commercial plan.

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. Improved thermal performance of windings in flooded machines, and a better understanding of winding performance when operated with high dV/dt.

2. A better understanding of bearing wear rate for polymer based bearings when operated in dry and fully flooded conditions.

3. Design, build, and commission a linear test rig for testing fully flooded generators.

4. Achieve the target outcomes specified according to Affordability, Performance, Availability and Survivability.

5. Refinement of the design tool to include reliability analysis, LCoE, and an improved thermal model.

6. Design Case Study reports for three developers: Carnegie, Albatern and Laminaria.

7. Technology and Commercial Roadmap, with a plan for a Stage 3 application.

1.2 Description of Project Technology

C-Gis 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

NGenTec's PMG is made up of light weight stator and rotor modules (See figure at bottom of page). 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 NGenTec's 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. NGenTec's PMGs do 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.

NGenTec's 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 NGenTec 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 NgenTec 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

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 demonstrator 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 as follows:

WP1 - Cooling System – CFD tools were used to investigate the cooling effect of a fully flooded generator. Different airgap geometries were considered: combination of smooth and salient surfaces on both stator and translator (Figure ..). A salient surface will introduce more turbulence, which has a greater impact on heat transfer. The coils could be fully potted in epoxy, which is good for protection, or partially potted allowing the cooling fluid to get closer to the heat sources, or not potted at all so that the copper is in direct contact with the seawater. A design was developed for each concept to allow modelling and comparison in later tasks. The CFD modelling was used to provide more accurate heat transfer coefficients for use in the design tool. Based upon the temerature of the windings the reliabilituy and lifetime of the windings was estimated using manufacturer's data.

WP2 - Bearing System - the choice of bearing system was based upon polymer bearing materials. Thordon Bearings have developed a product that has been used in main shaft propeller bearings using seawater lubrication. In order to learn most about bearing materials it is best to undertake experimental testing in a relevant environment. A linear bearing test rig was designed and built in which the material can be loaded and operated in either dry or wet conditions. A number of samples have been tested both in dry and wet conditions up to an equivalent of 500km of travel, which in a real device is estimated to be 6 months of operation. Based in the wear results it will be possible to determine lifetime and hence maintenance intervals for each bearing material. The main outcome from this task will be a look-up table providing guidance on wear rate vs load vs environment, which can be incorporated into the design tool.

WP3 - Marinisation - Testing In this WP we will perform tests on individual components within the winding to ensure full reliability within the winding when operated in sea water for the final prototype test, and hence minimise risk to the final outcomes of this project. The winding is the weakest sub-assembly of a fully flooded generator. Ensuring that the manufacturing process to seal the windings and their connections is well understood will be critical to successful outcomes of the project. Different potting materials already tested in previous projects, where manufacturing quality was not really essential, will be tested using the environmental test facilities at Edinburgh. Previous work has shown that there is a capacitive effect when coils directly immersed in sea water are switched continuously with high dV/dt as would be experience in a real system with the generator connected to a power converter operarting in pulse-width modulation mode. Coils potted in different materials, and with different connection methods will be tested for 8 hours continously in sea water undergoing high dV/dt switching. After each test the coils will be tested for high voltage to check insulation integrity and will be inspected using a microsope for changes to the coil surface which may indicate degredation leading to ultimate failure. The tests will be repeated until the coil fails, if at all. For each potting compound 5 different coils will be made, and we will focus on 2 different compounds - epoxy that has been used in the past and exhibits good thermal characteristics and silicon, which showed to be the best compound in terms of dV/dt operation, but not so good thermally. The main outcome from this test will be an understanding of the requirements for manufacturing quality, most appropriate potting compound, and terminal connection method for marinised operation.

WP4 - Prototype and Test Rig Design & Build - The main function of the test rig is to allow wet testing of the prototype module under dynamic electrical and environmental load conditions. UoE's existing linear test rig will be adapted to include wet testing and load emulation. A specification of the test rig, instrumentation and the load emulator will be drawn up in consultation with the sub-contractor, Fountain Design Ltd. UoE's existing linear test rig simulates heave motion. In order to emulate the reaslistic motions of a device like a buoy and apply external loads a load applicator will be designed and included within the test rig. Instrumentation will be used to measure temperature, applied load forces, electrical generated load forces. All instrumentation will be controlled using National Instruments hardware and software, of which UoE already has experience. The exisiting UoE test rig has a permanent magnet translator from the CT Marine Accelerator project, and will be used in the prototype to save cost and time. Since the project is focussing on thermal performance of the windings, and bearings the PM translator design will not affect the outcomes. In addition to the large test rig a smaller test rig was also built (not in the original WP plan) to make it easier and cheaper to test a wider range of winding topologies for thermal performance.

WP5 - Test Programme - A test programme will be designed to ensure maximum learning in all aspects of investigation. Machine and bearing test standards will be followed accordingly. For each winding module tests will be performed under two different displacement regimes: sinusoidal motion of varying amplitude and random motion, representing monochromatic seas and real mixed seas respectively. The machine will be loaded in both cases at part and full electrical load, as well as envinronmental loading at the gimble. A clean salt solution will be used for the wet testing initially to ensure that the environment is controlled, which will ensure that any wear out issues are not caused by other contaminants that might be found in real sea water. Such controlled testing will allow any wear or degradation to be collerated with operation in a salt water solution only. In the last month of testing additional contaminants will be added such as sand or mud with grit to observe the impact of a real sea environment. Throughout testing temperature, forces, voltages and currents will be monitored, with analysis of these results taking place on a continuous basis to compared with modelling/design results from WP1 & 2.

WP6 - Reliability Analysis - This WP will model (the infludence of downtime on) energy production and O&M costs so that they can inform the PTO design and feed into WP7 Levelised CoE Analysis. An existing Strathclyde model – developed at the EPSRC Wind & Marine Energy Systems CDT - will be used to determine O&M costs and downtime through calculating accessibility and power production of a wave farm by using a multivariate auto-regressive climate model and a Markov Chain Monte Carlo failure model. Necessary adjustments to this model will include failure rates, repair times, device power production capabilities, vessel day rates and vessel capability limits. Failure rates of the different PTO subsystems and for the assumed device will be estimated, using OREDA data, other published sources and inputs from the earlier WPs (such as MTTF based on wear rates). Where failure rate data is from other applications/loadings, then adjustments factors will be used (see Thies et al.) including consideration of projected thermal and loading duty cycles. Different runs will be set up to investigate the effect of the number of parallel generator and power converters on availability and O&M costs. These outputs are used in WP7.

WP7 - Levelised Cost of Energy Analysis - This WP will model the LCoE for a typical wave farm using devices incorporating this PTO. The aim is to reduce the LCoE. Initially, the design tool will be amended to incorporate assumed baseline device capital costs, lifetime, fixed charge rates, O&M costs and and an input probability distribution for the wave farm and its location. The design tool is used to optimise the independent design variables to reduce this LCoE. Later on results specific to the PTO (e.g. from WP6) will be fed into the LCoE analysis, allowing the different designs of this PTO to be compared.

WP8 - Design Tool Refinement - This is a continuous WP in which the design tool is refined based upon results from WP1 and WP2, as well as experimental results from WP5. WP1 will provide accurate heat transfer coefficients to be used in the lumped parameter thermal model defined in the design tool. WP2 will provide more accurate structural and bearing design data. The design tool will be used to design a full-scale device for a heaving buoy at say 100kW, which will feed into WP4 and 5. It is anticipated that results from WP4 & 5 will lead to further refinement of the design tool based upon experimental results.

WP9 - Commercialisation - Based on all results from previous WPs, we will present a final optimised design including reliability and LCOE for particular design case studies of devices that have been tested at sea and thus are at a particular stage of development which provides C-GEN with a commercial pathway as part of its development. Based on this a Commercialisation Roadmap will be produced to take the PTO technology to the next level, with the aim of identifying partners for a Stage 3 proposal.

1.4 Project Achievements

The main project achievements can be summarised as follows:

1. **Validation of Winding Performance in Fully Flooded Generators** – Investigation of windings operating in a fully flooded environment has not been published before as far as the investigators are aware. Results were generated for a number of different stator and translator surface topologies, a combination of smooth and salient, in both dry and wet conditions. The results showed clearly the positive impact of fully flooded operation in terms of the thermal performance – over 100 times improved heat transfer in water compared to air. In addition the modelling results showed the impact of the surface topology with a salient structure providing twice the heat transfer compared to a smooth surface topology on the stator and translator. Experimental results support these findings, thus giving confidence that the concerns over thermal performance observed in the 50kW demonstrator funded by Carbon Trust can be successfully overcome through fully flooded operation. Additional drag forces were investigated and found to be negligible and hence of no concern.

   The improved cooling performance of fully flooded windings allows the use of much higher current densities. With natural air cooled machines a current density of 4 A/mm^2 is typical, but results from the mini test rig suggest that more than 18 A/mm^2 could be achieved (wire diameter is 0.75mm, at a current of 8A). As a result of this improved cooling the power density could be increased by about a factor of 5, which will reduce material costs per kg, but at the expense of efficiency.

2. **Successful Experimental Demonstration of Component Testing under Wet Conditions.**

   Three different experimental test programs were undertaken during the project to better understand the performance of key components in the generator, namely windings and bearings. Three test rigs were built: bearing test rig, winding marinisation, and a large linear test rig for testing up to 6kW. In addition a mini-linear test rig was built to supplement the winding marinisation tests. The test programme has been successful, in that the tests completed so far have validated the expected findings from current and previous modelling and experimental work. Test results from the mini-test rig have demonstrated the beneficial impact of fully flooded operation on thermal performance of windings, supporting the findings in WP1. The bearing tests are providing data on wear rates under dry and wet conditions, providing estimates of lifetime to feed into the design tool.

   Although the experimental testing has been successful, it has not gone as smoothly as expected and not all the testing has been completed.

   There were delays with the large test rig due to the complexity of the design and in particular the load applicator, which has not be attempted before. Once the test rig was installed a mechanical failure occurred during the initial no-load tests, which has now been rectified, but also led to removal of the load applicator. Since then there have been no further problems and no-load and load tests have been completed successfully.

   The bearing test rig is driven using an actuator supplied by a compressed air supply, which conveniently was available in the lab. However, the air compressor has broken down several times since testing began, and even the installation of a new compressor has not helped. This issue is beyond our control, and really the only way to solve it would have been to buy a dedicated compressor, but this was beyond the available budget. However, we have still managed to complete 500km of tests on 5 different samples in the dry and are currently running wet tests. The bearing test rig can be run unattended 24/7, so we will continue running the tests beyond the end of the project.

The mini test rig was available from month 6, but we decided to focus on the large linear test rig as the mini-rig was not really part of the project. However, over the last month results from the mini test rig have proved very useful, and we should have prioritised the mini rig testing earlier, as there have been fewer mechanical issues with it.

Overall I think it was ambitious to implement the original test program with 3 new test rigs, but the results produced thus far are enough to justify the rationale for the key activities undertaken, and have provided enough data to give confidence in the design of C-GEN for fully flooded operation. Now that we have the test rigs, we will continue to run tests and collate data, which will be useful for future projects including a potential Stage 3 project, if successful.

3. **Refinement of the Design Tool for Marinised Design of C-GEN** – the design tool has been verified in the past, but really only in the electromagnetic design of the generator. The main weakness has been in thermal modelling, and hence predicting temperature rise. Much of the accuracy of the thermal model relies on accurate heat transfer coefficients, which have now been provided from WP1. In addition reliability and LCoE tabs have been included in the design tool. In terms of CAPEX of the PTO, the tool simply uses the material costs of the generator, including an estimate of the structural design. No manufacturing costs are included, but as a rough estimate we have used a 60/40 split for CAPEX material costs/manufacturing costs based on a discussion with one of the industrial partners, Carnegie Wave Power Ltd. From the 1st December we have started another project related to C-GEN to determine an accurate CAPEX manufacturing model of the generator with Hayward Tyler. This partnership has arisen as a result of WP9 activity in industrial engagement. The project is funded by the University EPSRC Impact Accelerator Account, and ends on 31st March 2017. A manufacturing CAPEX tab will then be included in the design tool based on Hayward Tyler’s experience in machine manufacturing.

4. **Engagement with industry –** WP9 focussed on exploring relationships with device developers, OEMs and the supply chain in order to inform the current Stage 2 project and to take the technology to the next level, Stage 3. Successful engagement with the industrial sector is very important for the further development of this technology in the marine sector, as the current lead partner (UoE) is not the most appropriate to commercialise the technology – clearly, UoE does not have commercial manufacturing experience.

   We had fruitful discussions with 3 device developers **–** Carnegie Wave Power, Albatern and Laminaria, all three of which have undertaken sea testing. These discussions led to design case studies in the case of Carnegie and Laminaria, and a concept study for Albatern, including confidential data on device characteristics for the design study. Discussions with Albatern also included options for sea testing in Stage 3 at their own specific sites on the West Coast of Scotland.

   Discussions with Hayward Tyler and their sister company Severn Energy Drives has led to a new project to develop a manufacturing cost model for the design tool, to better inform LCoE calculations. Another aspect of this additional project is for Hayward Tyler to better understand the requirements for developing manufacturing facilities for C-GEN, with the aim of Hayward Tyler becoming the preferred manufacturer of C-GEN, and as such this would take C-GEN closer to commercialisation.

Supply Design is an SME based in Rosyth, specialising in modular power electronic systems. As part of the technology roadmap for C-GEN integrating the power electronics into the generator modules is an attractive option in terms of developing standard modules, manufacture, assembly and O&M. Based on a number of meetings Supply Design is interested in being a partner in a Stage 3 application.

Overall the industrial engagement has been very successful providing UoE with potential partners for a Stage 3 project, but also partner interested in taking the technology forward to commercialisation.

In the original application the IP owner of the technology, NGenTec, was responsible for WP9 and industrial engagement, but the company decided to withdraw from the project due to winding down. This provided a dilemma for the project team, as WP9 was an important part of the project and was also responsible for the Design Case Studies. In addition as owners of the IP, it would make a future Stage 3 project very difficult if the IP were sold to another 3rd party. Despite this setback, the remaining partners divided WP9 tasks between them and reassigned resource, which has worked well. UoE purchased the IP to bring it back under university ownership to ensure maximum opportunity for further commercial exploitation and a Stage 3 application.

5. Design Case Studies

Three design case studies were undertaken to investigate the feasibility from both a technical and economic view point of C-GEN technology within specific devices. Device developers were chosen that had a track record of sea trials, so that the C-GEN development plan could be aligned and run in parallel with the device development plans, so that with correct timing C-GEN would be ready for deployment on a full-scale device.

All case studies were completed using the refined design tool, which included the new LCoE, reliability and thermal plug in modules.

Case Study 1: Carnegie Wave Power Ltd. – Carnegie have successfully demonstrated three 300kW devices off Garden Island in Australia. The company is developing the so-called CETO 6, a 1MW device for deployment at WaveHub in the SW of England. A design study for the CETO 6 was undertaken using device characteristic data provided by Carnegie. The optimum design resulted in a C-GEN device of mass

17,139 kg (active and estimate of structural mass), average efficiency 71%, final cost of energy of £144/MWh (Chozas' LCoE tool).

Case Study 2: Laminaria – The company has successfully demonstrated a 200kW device. With the Laminaria device the heave and surge motion is converted into rotary motion, so that a rotary generator is required. A design study was undertaken using device characteristic data provided by Laminaria. The optimum design resulted in a C-GEN device of mass 5,796 kg, average efficiency 93.2%, final cost of energy in the range of £157/MWh to £135/MWh, depending upon number of stages (Chozas' tool).

Case Study 3: Albatern – a concept study was performed for Albatern. Albatern's current method of PTO and interface between the PTO and device is undergoing change as the technology is scaled. For this reason no device characteristic data was available in order to provide a detailed design study. We will continue to work with Albatern to produce a detailed design study when new data is available.

1.5 Applicability to WEC Device Types

C-Gis compatible with a number of different device types as outlined below, and as part of industrial engagement in WP9 companies have been identified as potential partners.

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 Carnegie Wave Power Ltd, Laminaria and Albatern , all of whom have engaged with the Stage 2 project, and are interested in being partners in a Stage 3 application. A design study has been completed for Carnegie and Laminaris, and a concept study for Albatern.

2. **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. No company has been identified.

3. **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 2 project has focussed on linear generators and hence no developer has been identified. Oceantech could benefit from C-GEN, but there has been no contact.

4. **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 Stage 2 has focussed on applications requiring linear generators.

5. **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. Carnegie's device is submerged, and could be considered as this device type.

6. **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

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 LCoE and CAPEX are £150/MWh and £500k/MW respectively.

- **Outcomes**

Generator CAPEX: Based on the Carnegie case study for 1MW, the active material costs are broken down in Table 1 (copper £20/kg, steel £3/kg and PM £36.10/kg, Aluminium £8/kg, Epoxy £10/kg). These costs do not include any manufacturing cost, but based on discussions with industrial partners, a 60/40 split (material/manufacturing) has been assumed, giving a total generator CAPEX of £416,881.

Steel	£23,002
Copper	£38,130
Magnet	£184,103
Structure	£4,893
TOTAL	**£250,129**

Table 1: Breakdown of active material costs

LCoE – using the above CAPEX and the WES LCoE tool for a 1MW device the LCoE calculated is £147/MWh, which is line with the value calculated from the Chozas tool. If the PTO CAPEX is changed from £250k to £1000k, the LCoE varies from £130/MWh to £173/MWh. The C-GEN PTO CAPEX is not a barrier to achieving a target LCoE of £150/MWh.

Performance

- **Target:** In this project we aimed for an average PTO efficiency across all loads of at least 90%.

- **Outcome:** For the two case studies the average efficiency across ¼ to full load are as follows:

  1. Carnegie : 71 % average generator efficiency.

  2. Laminaria: 93.2% average generator efficiency.

- **Comment:** The target efficiency was based upon a design of a 2MW machine for AWS done as part of the Carbon Trust Marine Accelerator project. Efficiency is a function of force, current and velocity, so that devices with different characteristics will result in a different efficiency profile. For the AWS the peak velocity was 2m/s, and in the case of Laminaria the rotational speed was 25rpm, both of which are acceptable for generating efficiencies in excess of 90%. At velocities lower than 1m/s the machine design becomes more challenging and the efficiency decreases, as shown in the Carnegie case.

  However, machine designs are not optimised according to efficiency, but are optimised for LCoE. Given that both devices with C-GEN generators result in an LCoE values close to the £150/MWh target, the overall system needs to be optimised not just the efficiency of the PTO.

Availability

- **Target:** The aim is to increase the possible range of availability in the range 75% to 90%. This will be determined through working with developers in WP9 as part of the Case Studies, and knowledge gained from prototype design and reliability analysis in WPs 5 & 6.

- **Outcome:** For the generator, reliability and lifetime analysis of the windings and bearings has shown:

  (i) The winding lifetime will be in excess of 100,000 hours of continuous operation because the temperature of operation is significantly lower than the rated temperatures of the insulation.

  (ii) The bearing life could exceed the equivalent of 5000 km or 5 years of continuous operation under the load conditions tested in the lab, which for the generator on its own are appropriate. If the generator can be isolated from the environmental wave loads, then we believe such a lifetime can be achieved.

  The overall availability depends upon the numerous components in the rest of the device, but given the experience of the components being investigated in the C-GEN technology, we believe C-GEN will assist in achieving an availability in excess of 90%. In our models an availability of 92% was used, which is less than that used in the WES LCoE tool.

- **Comment:** Further discussions with device developers are required to develop predictive maintenance strategies for the complete device including the PTO, and thus obtain a more informed approach to availability.

Survivability

Target:

- Maximum to average mechanical load ratio = 10, based upon the peak force produced during a short circuit fault on the generator.

- Maximum to average electrical load ratio = 5, based upon the peak current during a short circuit fault.

Outcome:

- **Mechanical survivability –** no actual physical tests were completed on the winding components, but the method of manufacture is the same as the 1MW demonstrator, on which physical force tests to emulate a short circuit condition were undertaken resulting in no failure.

- **Electrical survivability –** thermal performance in the flooded environment shows very low operating temperatures (< 20 °C) at normal loads, which is significantly lower than the insulation ratings. During a short circuit condition, in which the current could by 5 times that of nominal tests showed that the winding temperature remained well under the insulation and epoxy thermal ratings.

1.7 Communications and Publicity Activity

There was no major drive to promote the technology to the public, or through academic papers etc, because the time scale of the project did not provide the opportunity to do so. Final results were not really generated until the last quarter of the project. With these results we will be producing papers as follows:

1. European Wave and Tidal Energy Conference, Cork 2017 – submit paper : Performance of windings in fully flooded linear generators for Wave Energy Converters.
2. All Energy, May 2017 – submit paper, C-GEN – a direct drive generator technology for marine renewables.
3. Ocean Energy Europe, 2017 – submit paper or poster.
4. Journal papers – IMechE or IET :
    a. Direct Water Cooling of Air-cored Windings in Direct Drive Renewable Energy Applications.
    b. Electrical and Mechanical Design of Flooded Linear Direct Drive Generators for Marine Energy Converters.

However, UoE has been active in promoting the technology to industry in order to commercialise the technology, as part of WP9 activities.

1.8 Recommendations for Further Work

All developments in the C-GEN technology, including the Stage 2 WES project have focussed on the generator including design, manufacturing methods, & component operation in the real operational environment. In order to integrate and operate the generator as part of a real device more work on the following aspects is required all of which have been included in the WES Stage 3 application:

1. **Power conversion**: Power electronic converters are required to interface the variable speed generator to the grid in order to provide fixed voltage and fixed frequency. Only a limited amount of work has been undertaken on the C-GEN technology – a 3-phase AC-DC-AC Voltage Source Converter (VSC) was used on an early rotary prototype. C-GEN has characteristics very similar to a standard permanent magnet synchronous machine, and so operation with a standard VSC should not be an issue. However, there is an opportunity to develop a more integrated and modular approach to the power converter design in line with the modular design philosophy of the generator itself. In Stage 3 it is proposed that there are two parallel streams for power conversion: (i) apply standard VSC technology for the full scale demonstrator; (ii) develop a modular power converter solution integrated into the machine stator modules.
2. **Condition Monitoring & Predictive Maintenance**: In order to provide effective O&M strategies condition monitoring plays an important role. For the generator, winding temperature, bearing loads and wear, vibration need to be measured and used in health monitoring as part of a predictive maintenance strategy. Winding temperatures will indicate the insulation integrity; bearing loads will give an indication of bearing life; and vibration will provide an indication of potential fatigue problems in the generator structure. Predictive maintenance is necessary in order to optimise availability and ultimately LCoE. As part of this techniques for replacing faulty modules are required to minimise downtime, which is most likely to take place onshore, but perhaps methods for offshore replacement on a boat should be investigate and how this would impact the design and assembly of the modules within the generator.
3. **Control:** C-GEN with power converter is an integral part of the complete wave energy system. The power

converter has two functions: (1) to optimise generator output and (2) to connect to the grid ensuring compliance with grid codes. Some work has been done on the use of the generator and power converter for controlling the performance of the device itself, but this leads to an overated electrical generation system. There is an opportunity to work with device developers to investigate what role the generator and power converter can play in overall device system control to supplement other control mechanisms used in wave energy systems. Control was beyond the scope of the current WES project, as it really requires input from developers, which will form part of a Stage 3 application.

4. **Manufacturing:** up to now one-off machines have been designed and built using labour intensive manufacturing and assembly techniques. Such an approach is perfectly acceptable for prototypes and demonstrators, but in order to reduce costs more automated or streamlined techniques are required for component manufacture and their final assembly. UoE is working with Hayward Tyler on an EPSRC Impact Accelerator project to make a start on this additional challenge, which is key to cost reduction and ultimately full commercialisation.