WaveDrive

WES Power Take Off
Stage 2 Project
Public Report

Trident Energy Limited

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

The WaveDrive project was commissioned by Wave Energy Scotland as part of their Stage 2 Power Take Off (PTO) call in 2015. The project aimed to deliver an improved design of an advanced Linear Generator (LG) for wave energy convertor applications. The LG under development consists of a magnet stack, armature, and bearing assembly. The WaveDrive project also considered the EC&I interfaces associated with LG control, and the design and definition of a test rig with the ability to provide instantaneously variable real-time generator control facilitates the adoption of sophisticated control algorithms to maximise the energy captured by WECs in irregular seas. This improvement is a step beyond the regular wave (sine wave) testing that has taken place within earlier Trident LG concepts.

The project ran from January to December 2016, with the final technical deliverables being completed and submitted at the beginning of November 2016.

The LG technology is owned and developed by Trident Energy Ltd who lead the project. The consortium was formed to bring together vital expertise and knowledge from key partners. The other partners in the project included:

- 42 Technology (42T) – responsible for the optimisation design of the linear generator.
- The University of Warwick (UWAR) - responsible for the electrical control and instrumentation.
- West Coast Wave Initiative (WCWI) – responsible for the hydrodynamic modelling.
- Enercro – responsible for the modelling of the linear generator.
- Energy Technology Centre (ETC)- responsible for the design of the test rig.
- Technology from Ideas (TfI) – responsible for the design of the spring and elastomer LG end-stops.
- SgurrEnergy (SGR) – responsible for project management and to oversee the delivery of the project. Also responsible for engineering review.

Trident Energy (TE) was the leading partner in the WaveDrive project. TE is the recognised leader in LG technology for wave energy applications and has existing intellectual assets related to numerical modelling and design & manufacture of previous LG prototypes including a portfolio of LG-related patents.

42 Technology (42) is a technology innovation and product development services company of around 40 engineers and scientists. The principal contributor from 42 was Alan Mackay. Alan was previously the Chief Technology Officer for TE, responsible for leading the design, performance assessment, manufacture and test of the company's direct drive linear generator technology and supporting systems.

The University of Cambridge (UCAM) was originally noted on the WES Contract, however, key personnel from the University moved to the University of Warwick (UWAR) within a month of the WES contract being executed. This led Trident Energy to place a contract with the UWAR, to secure the skill of the relevant and experienced individuals and access to a broad range of expertise including design of power conversion electronics needed for

the generation of electrical power from wind and waves. The WaveDrive project builds on the existing successful academic collaboration arrangement between TE and UCAM. The project allowed UWAR to deliver a programme of control system enhancements identified during the last prototype tests and hence provide continuity for the UWAR Post-Doctoral R&D personnel supporting TE.

West Coast Wave Initiative (WCWI) is part of the University of Victoria, BC. The group has developed industry leading wave energy resource assessment methods, numerical simulation tools for Wave Energy Converters (WEC) and numerical grid integration toolboxes. WCWI's expertise played a crucial role in the WaveDrive project by identifying PTO requirements against the required range of wave characteristics for a range of WEC devices. This information fed directly into some of the LG detailed design decision process.

Engineering Technology Centre (ETC) is part of the UK's innovation system and provides a range of development and test facilities to allow developers to de-risk technology development through robust testing in a controlled environment. ETC's involvement was the design of a test rig capable of fully simulating the irregular wave environments and the forces the advanced LG design will experience in a WEC device. This design will be taken forward and fabricated as part of test work within a planned WES Stage 3 project.

SgurrEnergy Limited (SGR), part of Wood Group, is a leading multi-disciplinary engineering consultancy specialising in renewable energy. SGR has a highly qualified team of over 200 engineers and consultants with extensive UK and international experience supporting renewable projects in over 90 countries across six continents, including considerable experience in the marine renewables sector. SGR was responsible for engineering review and project management of the WaveDrive project, including managing the reporting and dissemination elements.

Technology for Ideas (TFI) has specialist knowledge in end stop design acquired largely through its work with WaveBob technology assisted this project with detailed design of the spring and elastomer end-stop for the PTO testing on the ETC test rig.

The WaveDrive project therefore had a highly experienced complement of partners, contractors and advisors ensuring the best prospect that the outcomes were delivered to WES, in an optimum manner and for the benefit of the sector as a whole.

The LG & associated control technology has key attributes directly related to the scope of the WES programme. The project was to be measured according to the WES metrics of Affordability, Survivability, Availability and Performance, which were set at the outset of the project and are discussed in greater detail in Section 1.6. The high level targets were:

- Increased power output per kg of mass employed in the design and higher power density in comparison with the TE5 prototype.
- 20% higher power output at 1m/s in comparison to TE5.
- Intervention period of 1 year or more.
- 20-year operational life.
- Technology agnostic - Applicability to a wide range of wave energy converters.

1.2 Description of Project Technology

The WES programme concerns the development of emerging designs and components to ensure efficient and effective long-term cost reduction as well as to achieve high levels of reliability and survivability in harsh conditions. LG and associated control technology is an emerging technology which has the potential to address many of the challenges that WEC developers have faced with their existing PTO systems and hence make a significant contribution to cost reduction.

The Trident Energy LG consists of a magnet stack, armature and bearing assembly, as show in Figure 1. The WaveDrive project developed the detailed design of an LG offering significant improvements over previous iterations of the Trident technology within the areas of Affordability, Survivability, Availability, and Performance.

Figure 1: Trident PowerPod II LG

The advantages of the direct drive LG design include its potential to improve the efficiency of energy conversion, through direct mechanical to electrical conversion of energy. The solution is modular in design, improving the manufacturability and transportability of the assembly and associated sub-components. The final LG is scalable, in that it can be modified with ease to effectively accommodate a range of different power output requirements.

1.3 Scope of Work

1.3.1 Original Scope

This section outlines the scope of the project that was put together for the proposal and identifies the flow of tasks through the project. The WaveDrive project set out with the aim of completing a detailed design of a direct drive LG, its associated control system technology and a test rig to perform rigorous LG testing and validate the performance of the advance PTO control system.

The project was split into a number of work packages (WP) outlined in Figure 2. The ambition was to design, develop and manufacture a PTO system that could be used by multiple different WEC developers. Therefore, it was vital to begin with assessing the various requirements that WEC developers would look for in a LG PTO. WP1 aimed to optimise the concept by collecting industry requirements from multiple WEC types. This involved gathering and collating all the WEC experience from within the partners of the project as well as from third party device developers. This was achieved by setting up a Device Advisory Board made up of the WEC developers.

This was essential in giving the project direction and focussing all the requirements towards the desired end-user customer base.

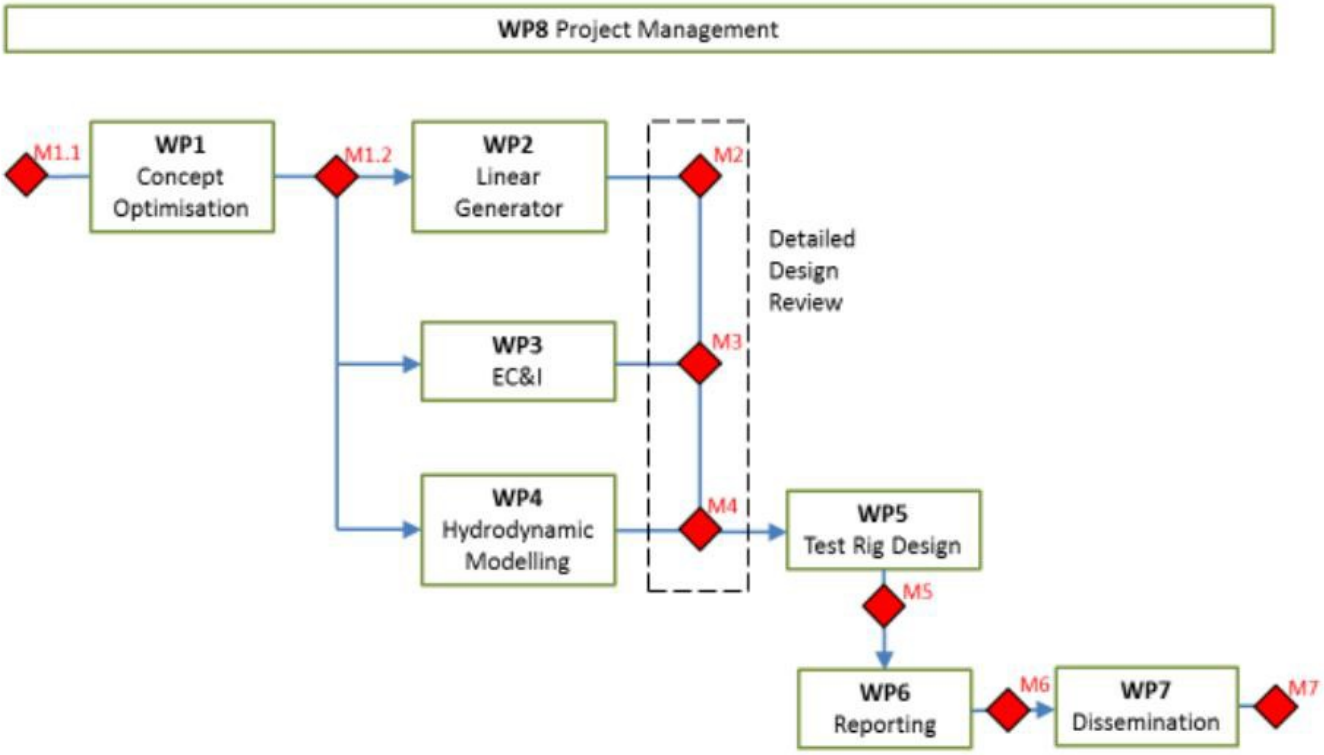

Figure 2: PERT (Program Evaluation Review Technique) diagram, showing breakdown of original work packages

WP2 was led by 42T and involved the design optimisation, concept and detailed design of the LG. 42 used TE's numerical modelling tools to optimise the design of the LG and simulate the LG performance against the requirements specification. WP2 included specific reference to the key challenges of reducing the air gap (the void between the magnet and coils), generator cooling across all conditions, and achieving high efficiencies across the required range of stroke lengths and velocities required by different WEC devices and sea states.

The UWAR (previously UCAM) led WP3, which involved the development of the electrical, control and instrumentation technology required to enable control of the LG in real-time and condition the electrical power output. WP3 focused on providing real-time control of the generator utilising high reliability solid state power electronics, rather than complex failure prone mechanical components. WP3 also utilised the existing relationships between TE, 42 to further develop the control methods and control algorithms.

WP4, led by WCWI, aimed to build a 6 degree of freedom (DOF) time domain model using the software package ProteusDS, with hydrodynamic parameters obtained (were appropriate) from WAMIT (industry software). The model included the mooring system setup, the WEC bodies and any interactions between multiple bodies, the hydrodynamic effects, and a simplified PTO system. Using this model, a dynamic link library (DLL) was built to directly couple this simulation to the provided LG PTO Simulink simulation. A number of different control strategies were investigated to determine the optimal system control strategy. The DLL transfers the position and velocity across the PTO, at a high time resolution, to the PTO model as well as the PTO forces, thus interfacing with LG and EC&I design (WP2 and WP3).

At the beginning of the project, it was assumed that WP2-WP4 would be carried out simultaneously by separate partners. The idea was that the design of the LG, Electrical Control & Implementation (EC&I), and the hydrodynamic modelling would be completed by the relevant partners 42T, UWAR and WCWI respectively. Once these were complete, the test rig could then be designed by ETC. The assumption that each partner would complete their designated work separately but simultaneously was unrealistic.

WP5, led by ETC, was the definition of physical onshore testing of the LG and its control technology. ETC utilised the outputs of the detailed design work to establish a test methodology, and test rig design which enabled the project to prove the operability, efficiency and performance of the improved LG technology. WP5 did not include the build of the test rig nor test of any LG equipment in this Stage 2 project.

WP6 (SGR lead) covers the final reporting of the project, to fully communicate the outcomes of the project and align them with the requirements of WES. The outputs form this work package will be the final project reports including a non-confidential lesson learned report and a confidential technical report including a risk register assessing outcomes against the target outcomes. As well as these, four extra outputs were produced in line with WES requirements to progress to Stage 3. These include: a FEED study for the Stage 3 prototype; preliminary design and fabrication plans for Stage 3; preliminary component / subsystem / system monitoring and test plan for Stage 3; and a commercialisation Roadmap for long term development of the technology.

WP7 (SGR lead) covers information dissemination. Dissemination has particular importance given the current status of the wave sector, and also the manner in which the WES programme is structured. TE and the partners will support dissemination activities following the completion of the WaveDrive project. Dissemination will be achieved through general outreach and profile building with direct contact with relevant organisations. Also TE is producing a technical data sheet informing on the scalability and performance of the enhanced LG PTO. The data sheet will be available as an online downloadable pdf file.

WP8 (SGR Lead) relates to overall project management. As well as overall project coordination, this WP included cross-project activities such as health, safety, environment, quality, data, communications and risk management. SGR were responsible for facilitating regular meetings between the partners and the organisation of the final deliverables to WES.

1.3.2 Revised Scope - Rescheduling of Deliverables

Early on in the project it was clear that the work breakdown and deliverables were not structured in the most effective way to ensure design outputs from respective partners would be available to feed input another partners' design process. It was therefore decided that a modified approach to the project deliverables was required. This involved moving a number of the deliverables around to better layout a path to completion. It was decided to advance the design of the test rig and push back the detailed design of the LG until the initial control system design work was completed. This restructuring helped to align the requirements of each partner and deliver a more in-depth final design of the LG without impacting on the end dates for the other technical deliverable, which completed on schedule.

1.4 Project Achievements

The WaveDrive project facilitated some key improvements in the development of the LG design, contributing to the overall objectives and successfully designing a concept that met the target WES metrics. Specific key

improvements in the TE7 design are summarised in "Deliverable D9.2 Technical Report and Risk Register – Confidential".

Overall, the WaveDrive project has been a success. Despite being delayed at the start due to administration issues, the project had a positive start. The kick-off meeting between all partners, including an advisory board, really helped define the aims and outcomes of the design. The redefinition of the deliverables part way through the project was essential in delivering a thorough detailed design which incorporated all the necessary requirements from other partners. This not only helped in delivering a highly detailed linear generator design but also enabled the project to be completed ahead of schedule, with the main technical deliverables being submitted at the end of October 2016. The lessons learned through the project were successfully resolved and these will be carried forward and incorporated in an application for a Stage 3 project.

The project could have benefitted from a dedicated Technical lead directing the interfacing of each WP. During the stage 2 application process it was envisaged that the team of technical partners would be a flat structure with all technical partners reporting into SgurrEnergy and Trident Energy for their respective deliverables. During the early stages of the project it became clear that the capabilities of the new linear generator design was the key input to several of the work packages. 42 Technology through Alan MacKay supported by Richard Crozier of Enercro and Alex Ridge of the University of Warwick had extensive knowledge and in particular the lessons learned from the earlier TE5 testing formed the fundamental basis of the design of the LG. In an unofficial capacity, Alan MacKay building upon his previous experience working at Trident Energy assumed the unofficial technical coordinator role during the project, leading the technical aspects of the LG design. For the Stage 3 application it is envisaged that a defined technical lead role will be noted in the application and project plan. This role will be responsible for the manufacture of the linear generator, fabrication of the test rig and subsequent testing programme. This will help direct the design and ensure all the requirements and interfaces are managed and addressed included in the testing of the LG.

1.5 Applicability to WEC Device Types

The Trident Energy LG has been designed from the outset to be technology agnostic, lending the LG design to integration within a number of WEC concepts. During the course of the WaveDrive project, focus was on having buoy point absorber type WECs.

The final deliverable of the hydrodynamic modelling work package investigated a different WEC type that may be ideally suited to LG implementation –a heaving float enclosed within a stationary circular cylinder. This concept is pursued as it offers the potential for an off-grid power solution. This type of WEC is a good choice for a linear generator PTO, as the motion is fully in one degree of freedom, the LG can be kept away from the sea water and its splash zone and the use of the fixed cylinder reduces the lateral forces and moments on the LG's bearing and structural assembly.

However, other WEC types would also permit the integration of the LG, including Attenuator type, Submerged Pressure Differential type, and OWC type WECs, which have been identified as WEC designs that offer significant opportunity for further development and integration of the LG.

1.6 Summary of Performance against Target Outcome Metrics

The WES programme concerns the development of emerging designs and components to ensure efficient and effective long-term cost reduction as well as to achieve high levels of reliability and survivability in harsh

conditions. Linear generator and associated control technology is an emerging technology which has the potential to address many of the challenges that WEC developers have faced with their existing PTO systems and hence make a significant contribution to cost reduction. LG & associated control technology has key attributes directly related to the scope of the WES programme. As is shown in Figure 3, the WaveDrive project has exceeded expectations with regards to the WES metric objectives set at the outset of the project.

Metric	Description	Target Outcome	Current Status	Target Met
Affordability	Increase output per kg due to increased power density.	Air-gap reduced from 5mm to <3mm.	The physical air gap between armature and magnet stack is nominally 2mm.	✓
Performance	Enhanced power output.	Output increase of 20% compared with TE5 model at 1m/s.	TE's numerical model predicts that the LG design offers up to 100% greater power output.	✓
Availability	Enhanced maintainability and operability.	Intervention period of 1 year or more.	The chosen solution requires minimum maintenance, with an intervention period of more than 1 year.	✓
Survivability	Established through detailed design.	Design for 20-year life, 1:50 year extreme conditions, EMEC climate.	The design has undergone structural assessment for peak loads predicted by modelling.	✓

Figure 3: WES Metrics

1.7 Communications and Publicity Activity

1.7.1 Press Releases

Two press releases were made during the course of the project:

- Trident Energy and 42 Technology make waves with improved PowerPod II design (3rd August 2016).
- AWS and Trident Energy collaborate to "control pressure" in new innovative wave energy device (6th October 2016).

1.7.2 News Articles

A number of news articles on the LG have been posted online. In addition to these links, it is anticipated that some articles will appear in print.

Cambridge News (online)
How a Cambridgeshire firm is paving the way for cheaper wave power
http://www.cambridge-news.co.uk/how-a-cambridgeshire-firm-is-paving-the-way-for-cheaper-wind-power/story-29642923-detail/story.html

Elektor magazine (online)
Cambridge men & power from the seas
https://www.elektormagazine.com/news/cambridge-men-power-from-the-seas

Ocean News and Technology (online)
Trident Energy and 42 Technology Make Waves with Improved PowerPod II Design
https://www.oceannews.com/news/2016/08/15/trident-energy-and-42-technology-make-waves-with- improved-powerpod-ii-design

Electronics Weekly (online)
Turning waves into power, in Cambridgeshire.
http://www.electronicsweekly.com/news/research-news/turning-waves-power-cambridgeshire-2016-08/

Renewable Energy Focus (online)
Trident Energy and 42 Technology collaborate to improve PowerPod II design
http://www.renewableenergyfocus.com/view/44697/trident-energy-and-42-technology-collaborate-to-improve-powerpod-ii-design/

Elektor (Germany edition – online)
Wellenenergie Version 2
https://www.elektormagazine.de/news/wellenenergie-version-2

Elektor (Netherlands edition – online)
Mannen uit Cambridge & energie uit de zee
https://www.elektormagazine.nl/news/mannen-uit-cambridge-energie-uit-de-zee

Ocean News and Technology
Ocean Energy: Technology, Regulation, Current Projects, page 24, December 2016.

1.8 Recommendations for Further Work

The WaveDrive project set out to achieve the detailed design of a LG, control system and test rig capable of demonstrating significant advancement in state of the art. The project partners believe that the PowerPod II design solution represents a rigorous approach to the design and specification of hardware, software, and test materials. While the physical testing has not taken place, the WaveDrive project has developed an LG design and test rig in which to test the LG across a range of operating conditions. The partners therefore feel that this has aligned well with the WES objectives, and places Trident Energy and its project partners in a strong position to continue development within the WES framework

Fabrication of the test rig and LG will allow the currently subjective metrics (based on a design rather than on test results) to be physically demonstrated / tested. Outputs from a test programme will provide the evidence to support the anticipated advancement of the technology. Therefore the design for both LG and test rig merits support through the construction phase in order to thoroughly test the design in a state of the art test rig, which may also be suitable for use by other WEC developers and linear PTO solutions. The activities required to complete this will be presented within a Stage 3 proposal for the WES PTO call.