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# SUPERGEN MARINE ENERGY RESEARCH

**October 2011**



**EPSRC**

Engineering and Physical Sciences  
Research Council





# **SUPERGEN MARINE ENERGY RESEARCH**

## **Full Report**

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**October 2011**



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## 1 Introduction

The Engineering and Physical Sciences Research Council (EPSRC) Sustainable Power Generation and Supply (SuperGen) programme is the flagship research initiative shaping the future of the United Kingdom's energy research landscape. It contributes to the UK's environmental emission targets by conducting research that leads to radical improvement in the sustainability of the UK's power generation and supply. The first of a total of 13 consortia was launched in October 2003. The mission of these consortia was to establish a platform for the development of new and improved devices for efficient and sustainable power generation and supply. The research of the Marine Energy Consortium focuses on developing the potential for future exploitation of the marine energy resource.

### 1.1 Phase 1

SuperGen Marine Phase 1 (October 2003 – September 2007) brought together research staff from the Universities of Edinburgh, Robert Gordon, Lancaster, Heriot-Watt and Strathclyde. Together they undertook generic research with the following long-term objectives. To:

1. Increase knowledge and understanding of the extraction of energy from the sea;
2. Reduce risk and uncertainty for stakeholders in the development and deployment of technology;
3. Enable progression of marine technology and energy into true positions in future energy portfolios.

In order to meet these objectives, thirteen research work packages (WPs) were undertaken:

- WP1 Appraisal of Energy Resource & Converters: Environmental Interaction;
- WP2 Development of Methodologies for Device Evaluation and Optimisation;
- WP3 Engineering Guidance;
- WP4 Offshore Energy Conversion and Power Conditioning;
- WP5 Chemical Conversion and Storage;
- WP6 Network Interaction of Marine Energy;
- WP7 Lifetime Economics;
- WP8 Moorings and Foundations;
- WP9 Novel Control Systems for Marine Energy Converters;
- WP10 Full-scale Field Validation;
- WP11 Assessment of Testing Procedures for Tidal Current Devices;
- WP12 Economic, Environmental and Social Impact of New Marine Technologies;
- WP13 Dissemination and Outreach.

Phase 1 trained 13 PhD students that took up employment across the sector. The outcomes and publications of this work are recorded in a preceding monograph, copies of which are available to download at the SuperGen Marine website - <http://www.supergen-marine.org.uk/drupal/>

### 1.2 Phase 2

SuperGen Marine Phase 2 (October 2007 – September 2011) brought together research staff from the core Universities of Edinburgh, Queen's Belfast, Heriot-Watt, Lancaster and Strathclyde. The consortium included affiliate Universities of Durham, Exeter, Highlands and Islands, Manchester, Robert Gordon and Southampton. Together they undertook generic research with the following long-term objectives:

1. Increase knowledge and understanding of device-sea interactions of energy converters from model-scale in the laboratory to full-size in the open sea, subjected to waves and currents.
2. Build human and physical capacity to carry out research and development to address remaining and new challenges as the expanding sector works towards the targets set.
3. Internationalise its articulation, activities, perception and influence.

There were twelve work streams (WSs).

- WS1 Numerical and physical convergence;
- WS2 Optimisation of collector form and response;
- WS3 Combined wave and tidal effects;
- WS4 Arrays, wakes and near field effects;
- WS5 Power take-off and conditioning;
- WS6 Moorings and positioning;
- WS7 Advanced control and network integration;
- WS8 Reliability;
- WS9 Economic analysis of variability and penetration;
- WS10 Ecological Consequences of Tidal & Wave Energy Conversion;

WS11 Training and Development;

WS12 Dissemination, Engagement and International Articulation.

Through its Doctoral Training Programme, Phase 2 has trained over 30 PhD students. Many have taken employment in the sector with, for example Vattenfall, AWS Ocean Energy, E-on, DetNorskseVeritas, Garrad Hassan and Open Hydro. Many others have joined the research staff in universities across the UK and Europe.

Phase 2 was advised by an Industry Research Advisory Forum that included Marine Current Turbines; Open Hydro; Pelamis Wave Power; Ocean Power Technology; Scottish&Southern Energy; Scottish Power; EDF; E-On; NPower; ETI; Carbon Trust; EMEC; NaREC; Crown Estates; Scottish Natural Heritage.

Phase 2 collaborated with the following international partners: HMRC Cork - Ireland, TU Delft-Netherlands, Ecole Centrale Nautique Nantes-France, Dalhousie University-Canada, Oregon State University, Florida Atlantic University, UMass-USA; Universities of Osaka City and Hokkaido-Japan; Harbin Engineering University and Dalian University of Technology-China; National Sun-Yat Sen, National Taiwan Ocean University, National Chen Kung University-Taiwan.

### **1.3 Phase 3**

The Marine consortium secured continuation funding for Phase 3, supporting a further five years of research from October 2011, and this brings together staff from the core Universities of Edinburgh, Queen's Belfast, Strathclyde and Exeter. The consortium includes associate Universities of Plymouth, Heriot-Watt, Lancaster, Manchester, Swansea, Oxford and Southampton. Together they form the UK Centre for Marine Energy Research, whose core membership and management team will aim to ensure a joined-up regional, disciplinary and thematic effort to meet the challenges in accelerating deployment towards and through 2020 targets, and maintain the international brand image and UK world-lead in marine energy with the following long-term objectives:

1. Conduct world-class fundamental and applied research that assists the marine energy sector to accelerate deployment and ensure growth in generating capacity through 2020 targets.
2. Expand and operate an inclusive marine network of academic researchers, industry partners and international collaborators.
3. Continue to provide the highest quality of doctoral training and knowledge transfer in partnership with industry to build intellectual and human capacity for the sector.

This document consists of five sections and contains three appendices. Section 2 summarises research in Phase 2 over the second four years of the programme. The aims of the future research in Phase 3 are presented in section 3. The Doctoral Training Programme and Dissemination, Engagement and International Articulation are summarised in sections 4 and 5. Details of the individuals involved in the programme, abstracts of the research outputs from Phase 2 grouped by workstream, and then alphabetically, are contained in Appendices 1-3.

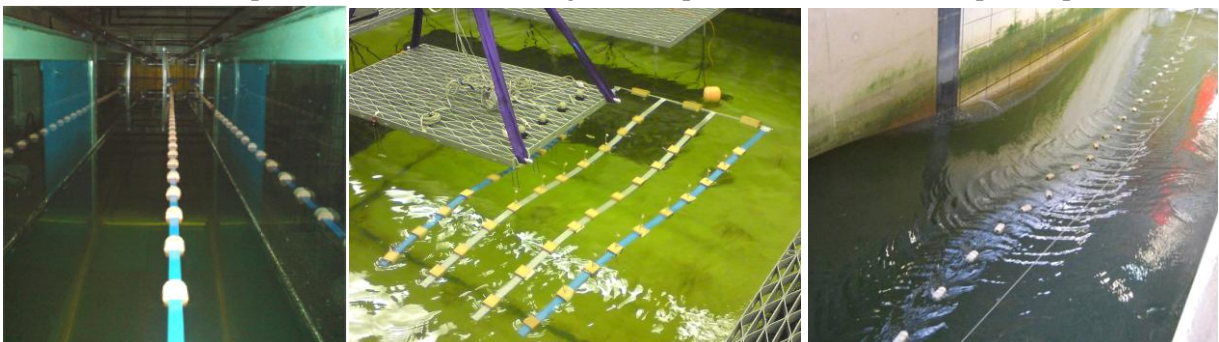
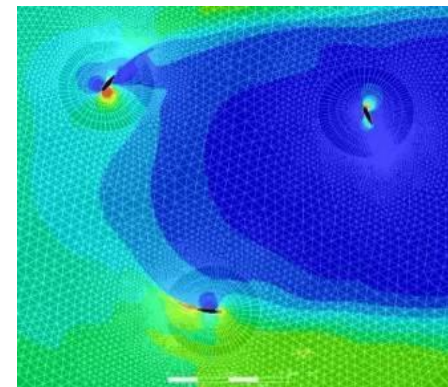
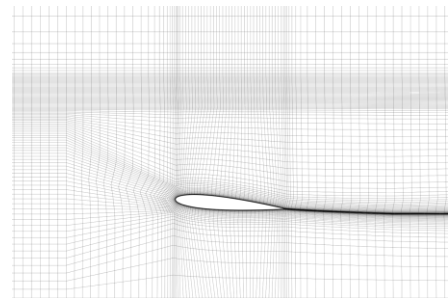


## 2 SuperGen Marine Phase 2

### WS1 Numerical and physical convergence

WS1 worked closely with WS3&4 to improve the theory for model-scale wave creation, refine experimental measurement, and extend device numerical CFD modelling to aid convergence between numerical and physical modelling. It has:-

- Produced and established the first peer-reviewed and accepted pan-European system of protocols for evaluation of wave and tidal energy converter performance. Invited paper WS1.3 introduces the collaborative European EquiMar project (coordinated by Ingram) where SuperGen partners have extended tank testing, resource characterisation, environmental and economic impact assessment methods to propose a European system of protocols for the equitable evaluation of both wave and tidal energy converters. Invited paper WS1.18 describes the best practices developed in SuperGen marine for the testing of wave energy converters. The new methodology described there has been included into the EquiMar protocols and is being considered for inclusion in the 62600 series IEC standard on tank testing.
- Developed and implemented new free surface and Cartesian cut-cell models for the open source “Code\_SATURNE” flow solver under a 5 year Framework Agreement with EDF R&D. In paper WS1.4 SuperGen authors present a new boundary condition treatment, based on the ghost fluid method, which exactly satisfies the zero-tangential shear condition at the free surface. The method builds on a level-set approach to locate the free-surface. Under the ETI funded PERAWAT project the methodology described in this paper is being incorporated into Code\_SATURNE. In paper WS1.17, a companion paper to WS1.4, the numerical method is applied to study the splashing of a secondary jet.
- Extended the Cartesian methods to capture and model sub-surface and free-surface fluid flow in wave energy converters and offshore structures. Papers WS1.1&16 describe the extension of the free-surface capturing methods developed by the authors, for the inviscid Euler equations, to solve the full Navier-Stokes equations, and their subsequent application to violent wave overtopping on sea walls, breakwaters and other coastal structures. The methodology described in the papers has also been extended for wave impacts on shoreline and breakwater installed OWCs and to the predecessor of the OYSTER wave energy converter. The second paper also provides a detailed validation of the use of free-surface capturing methods which utilise a Godunov-type method to capture the density discontinuity at the free surface.
- Advanced the science and practice of numerically modelling and physically measuring the creation and absorption of combined waves and currents. Papers WS1.12, 21 & 29 describe a consistent approach to the selection of control methodologies for absorbing wave makers. These papers highlight that the novel wave maker shapes can be tuned for optimal performance at one frequency while the control algorithm can be tuned for another, giving much enhanced absorption over a wider range of incident wave frequencies.
- Invented and developed the world-first floating wave-tape to measure wave shape. Paper WS1.20



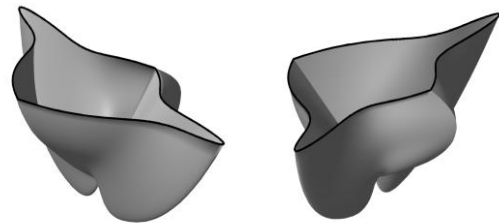
describes a world-first real-time floating fibre optic sensor, its data processing methodologies and software, and proof of concept field testing across a range of scales in European tanks. SuperGen staff won consequent funding from the UK and industry support from Measurand Canada to develop and exploit this technology.

- Co-invented and developed a dynamically calibrated laser wave gauge that has created a step change in the resolving of surface shape and motion in wave tanks. Paper WS1.13 describes another measurement technology to be created in and around SuperGen. Capture of reflected laser beams from the surface of waves in test tanks is now allowing the non-invasive real-time measurement of cnoidal waves and enables greater understanding of non-linear effects in tanks.
- Applied non-linear boundary element methods to model the response of complex collector shapes.

## WS2 Optimisation of collector form and response

WS2 developed and applied genetic algorithm techniques to evolve new shapes of wave energy converters that were tank tested to prove that they are better than those that human imagination or experiment could have suggested. Applying biologically inspired evolutionary design to device shape and performance, WS2 worked with WS7 and has:-

- Evolved novel device shapes for pitching/surging wave energy converters using genetic algorithms. Paper WS2.13 describes a strategy for optimisation of wave energy working surface shape, from a clean sheet, with no presupposition or human bias. Staff developed a parametric description of the wave energy collector geometry that is compatible with a wide range of CAD/CAM file formats. To reduce the size of the solution space that required to be searched, complex surfaces were generated from a small number of control points and their response tested rapidly within WAMIT to seek breed improvement or degradation that could be subjected to penalty in performance cost functions.
- Tested many radical new and perhaps unimaginable collector shapes for wave devices that can be bred into different forms for different wave climates. Descriptions of these usually intuitive collector shapes were initially visualised in software but then exported to a rapid prototype moulder to produce 1/64<sup>th</sup> scale models whose response and performance was tested and confirmed in the wave tank at Lancaster.
- Proved that GA based evolution can suggest new shapes of wave converters that could increase energy yield. Papers WS2.3, 9, 11 & 13 describe how the primary drivers of the cost function in the optimisation can be customised to include ambient wave climate and constraints on system variables to give a more realistic appraisal of each shape's performance. Constraints and variables were included in the algorithm itself so that the routine became able to optimise variables such as displacement limits and externally applied damping and stiffness, leaving greater freedom to accommodate non-linear effects that may not be included in the cost function itself. The formulation of the cost function has identified several aspects which need to be considered when evaluating the collector shapes. Statistical methods may need to be applied to obtain a truly representative equivalent of a sea state, in terms of the number and distribution of waves with different phase groups. Power extraction can only be simulated when some form of control is applied and implemented efficiently within the cost function. One such design is described in Paper WS7.6. The inclusion of secondary considerations, such as ease of manufacture or maintenance, can also be implemented within the genetic algorithm structure. However, maintaining the balance between the primary goal of energy absorption and such secondary considerations was shown to be critical. Differentiating between shapes when a more realistic, constrained regime is imposed on the optimisation became more difficult as only a limited number of collector shapes produced exceptional results and many were similar in performance. Better and best device shapes have been found to change by evolutionary processes to perform better in differing wave climates and all differ from the first-generation shapes currently at, or on their way to, sea.



### WS3 Combined wave and tidal effects

WS3 has extended the understanding of how the design of wave and tidal current generators is influenced by the combined actions of waves and currents. In addition to the core activity, the nature of the research has also enabled contributions to publications relating to resource assessment, marine energy policy and even tidal barrage applications. The workstream has worked very closely with WS4 throughout and its significant contributions have included:-

- Improved geographic resource assessment techniques leading, for the first time, to robust and, working in collaboration with Black & Veatch, increased estimates of the tidal energy productivity of UK coastal waters. These improved estimates are 50% higher than previously predicted.
- Paper WS3.1 and several predecessor papers from Phase 1 formulated a robust procedure used to assess tidal energy potential, taking into account the nature of the resource and energy extraction effects. It described, in detail, the formal, three dimensional nature of the tidal energy extraction process. Unlike the earlier publications, there was no dimensional simplification. This allowed the anomalous behaviour of tidal flows, subject to artificial extraction, to be assessed directly. Application of the methods in this paper allowed formal and rigorous resource assessment and physical environmental impact to be assessed.
- Advising UK policy formation on the opportunities for and constraints on developing the sector towards the 2020 targets for marine energy. Paper WS3.2 won the 2007 ICivE David Hislop Award for defining the enabling needs of the sector at a crucial time and the impact of underpinning research. Paper WS3.9 was communicated more widely in an invited presentation to the House of Commons Parliamentary Group for Energy Studies and presented a rigorous statement of potential for a marine industry and a clear identification of anticipated constraints to the development of both wave and tidal sectors.
- Development of a framework for environmental impact assessment, demonstrated by case study of the Straits of Messina. This has led to the first ever journal publication focussed on the interaction of tidal turbine arrays with sedimentation processes. Paper WS3.10 was the first academic paper to describe the procedures necessary to assess the environmental impact in the anticipated large scale tidal current developments of Crown Estates Rounds 1&2, specifically understanding the effects of energy extraction by machines in extended arrays and the direct physical consequence of this. Paper WS3.10 evolved after initial modelling of Messina, when it became obvious that effective modelling of the hydraulic conditions would require a broad understanding of the ambient conditions if the models were to be useful for wider development purposes.
- Collaboration with Bangor University (School of Ocean Sciences) leading to the first journal publication focussed on the interaction of tidal turbine arrays with sedimentation processes. Paper WS3.17 demonstrated for the first time that tidal energy extraction will alter the hydrodynamics of a tidal region, analogous to increasing the bed friction in the region of extraction. It identified that the energy extracted by tidal asymmetries due to interactions between quarter ( $M_4$ ) and semi-diurnal ( $M_2$ ) currents will have important implications for large-scale sediment dynamics. Simulations showed that energy extracted from regions of strong tidal asymmetry will have a much more pronounced effect on sediment dynamics than energy extracted from regions of tidal symmetry. Indeed this could lead to a 20% increase in the magnitude or bed level change averaged over the length of a large estuarine system, compared with energy extracted from regions of tidal symmetry. However energy extraction was still shown to potentially reduce the overall magnitude of bed level change compared to the un-developed site. This has serious implications for many intended development areas such as the Irish Sea and the Bristol Channel. Further work in this area has expanded the analysis to 2-d application and to additional generic geometries (e.g. around headlands and islands as well as estuary dynamics)
- Design and assembly of a multi-jet current injection system that allowed the exploration of wave-current interactions in existing wave tanks. This system can be installed, in principle, in any wave



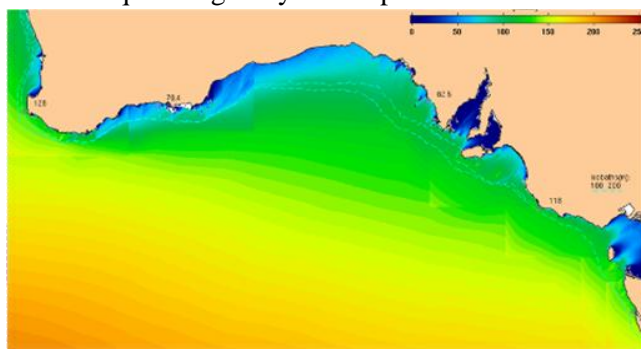
basin with depths beyond 1m. A parallel system has also been developed to give retrospective current capabilities in narrow wave flumes.

- Staff have field tested a novel  $1/10^{\text{th}}$  scale tidal turbine in Montgomery Lough in Northern Ireland. This has immensely increased appreciation and understanding of the flow in close proximity to a horizontal axis rotor and increased confidence for the development of a twin rotor system developed for the ETI PeraWatt programme.
- Created robust protocols, working with DECC, to evaluate marine energy systems in the MRDF.
- Provided advice, working with EMEC, on scaling issues for the new  $1/4$  scale “pre-EMEC” facility.
- Identified a key limitation of ADCPs for measurement of turbulent flow. Work will continue to understand and address this in collaborative research programmes.
- Analysed the variability of expected design extremes and common instantaneous wave-current interactions that have now been applied to the expected load patterns on a tidal current turbine. The approach is being further developed to consider the long-term resource characteristics, and hence loading patterns, assuming standard wave climates appropriate for early stage tidal turbine projects.
- Analysed the detail and interpreted the temporal nature of turbulence in tidal flows, including developing a quantitative appreciation of the implications of using Doppler profilers. This was initially based primarily on data from EMEC but has recently been extended in USA in collaboration with the University of Washington (WS3.24).
- Developed wave-current impact guidance to inform two separate strands of the developing IEC TC114 International Standards. The first considers appropriate means of data collection and analysis to characterise the resource. The second provides best practice guidelines on how to implement the resource characteristics identified in the context of device design through an increased understanding of the variability of load patterns at various different time-scales.
- Performed field tests in Strangford Lough that will continue to assess the influence of current on the behaviour of wave devices at a large model ( $1/10^{\text{th}}$ ) scale and enable the effect of marine current on the motions of freely floating bodies to be measured remotely.
- Designed and deployed a unique buoy and ADCP array off the North Cornwall coast specifically to provide support to the Wave Hub, additionally re-appraising wave climate data for the site.

#### WS4 Arrays, wakes and near field effects

WS4 has enhanced understanding of the interactions between individual devices in wave or tidal arrays, and how the arrays themselves interact with the hydrodynamic environment. It worked with WS3 and has:-

- Established new understanding of wake effects in tidal current turbine arrays. Paper WS4.1 described the application of CFD techniques to tidal turbines at model scale so that laboratory methods could be subsequently applied for verification before full scale data was available. Paper WS4.6 closed the modelling-experimental loop and gave confidence to the application of wake modelling methods for array interaction modelling of tidal current turbine arrays.
- Developed new experimental techniques for measuring multi-mode spectral waves in arrays. Paper WS4.27 reports a major step that allows greater understanding of the outputs from laboratory tests. Hitherto, robust, multi-mode spectra directional wave measurements have been difficult, if not impossible, to perform in laboratory facilities. This paper challenges conventional wisdom and shows how the pseudo random nature of laboratory waves can be used to the advantage of experimentalists and how the application of modified versions of techniques originally developed in the 1980s could be extended to enable a new generation of testing. In addition, paper WS4.25 details the analysis of a wave basin to determine its suitability for testing wave energy converter arrays and shows that the homogeneity of the wave basin is critical.
- Identified that the near-shore wave resource is far more energetic than previously realised. Paper WS4.5 was the first to relate the significance of the nearshore resource and introduced the 'exploitable wave energy resource' as a more realistic way of comparing the offshore and nearshore wave resource relevant to



energy extraction. It showed that the exploitable nearshore resource is only 23% less than that offshore even when there is a shallow sea bed slope such as in South Uist. The reduction is less where there the seabed is steeper. The analysis takes into account the directionality of wave power device arrays and highlights that using an omni-directional wave resource value and an unlimited installed capacity in wave power assessment is very misleading because it can make offshore sites look much more energetic than shallower nearshore sites.

- Developed the first spectral model that suitably represents wave energy converters. Paper WS4.19 reported on the development of a spectral model which incorporated a suitable representation of wave energy converters. It is an extension of a frequency domain model which includes non-linear forces without the high computational cost of a time domain model. A bottom hinged flap type wave energy converter was used in the analysis. The development of a spectral model of wave energy converters enables their inclusion in coastal modelling tools such as SWAN and Mike 21 SW leading to the modelling of environmental impact and energy yield of wave farms in the coastal zone. Paper WS4.20 analyses the accuracy of using phase-averaged interactions between wave energy converters and it is shown that except where the devices are very close to each other a phase-averaged representation is a reasonable approximation. Paper WS4.24 provides wave-tank validation of a spectral-domain model of an oscillating water column.
- Field tested a 1/10<sup>th</sup> scale novel semi-submersible tidal turbine in a dedicated open sea test site at Portaferry in Strangford Narrows in Northern Ireland, in association with WS3. In addition the tidal turbine was towed from a purpose built catamaran with an integral instrumentation platform to measure its performance in steady uniform conditions as well as mapping its wake. The steady state performance was then compared with that in real tidal flows.

## WS5 Power take-off and conditioning

WS5 developed design tools which incorporate structural, magnetic, thermal and electrical understanding, to allow cost effective development of next generation power take off systems for marine energy converters. It worked with WS7 and has:-

- Completed an analysis of hydrostatic bearing needs and designs for iron-cored and air-cored machines.
- A double-sided iron-cored permanent magnet linear synchronous generator in a direct drive system needs a bearing system that is designed to react against in-line drive forces and quadrature clamping forces between the stator and translator that are up to 10 to 20 times higher than the generators shear forces. Staff designed and built a wet linear test rig for assessing bearing materials for linear generators, in which the bearing materials are installed into a scaled linear generator and loaded with realistic magnetic forces. Papers WS5.7, WS5.9 & WS5.14 describe the design of novel fluid film linear bearings and the full-size structural loading and drive rig.
- Developed combined electromagnetic-structural-thermal design tools that optimise the design of low-speed direct drive generators. Papers WS5.11, WS5.14 & WS5.17 describe the tools developed, and WS5.33 illustrate how these tools were used to develop a novel lightweight permanent magnet generator.
- Integrated hydrodynamic models of buoys into the design optimisation of direct drive linear electrical generators, taking into account the electromagnetic and structural design. Electromechanical and hydrodynamic simulation was combined in paper WS5.21 to simulate the behaviour of a novel generator connected to a heaving buoy. Numerical models were driven by data derived from an electromagnetic finite element analysis and from the WAMIT to simulate the integrated system in the time domain.
- Analysed the thermal performance of generators in OWCs to show that generators could operate overloaded without exceeding the thermal limits, increasing the yield on investment. This work was done in collaboration with Wavegen. Papers WS5.11 & WS 5.22 reported a thermal model for an induction generator in an OWC where the thermal resistances used are found from steady state testing in the working environment. The cooling available in this application is inherently better than that



normally experienced by this type of generator and thus generators can potentially be under-rated to cost less, take up less room and run at higher plant capacity factors.

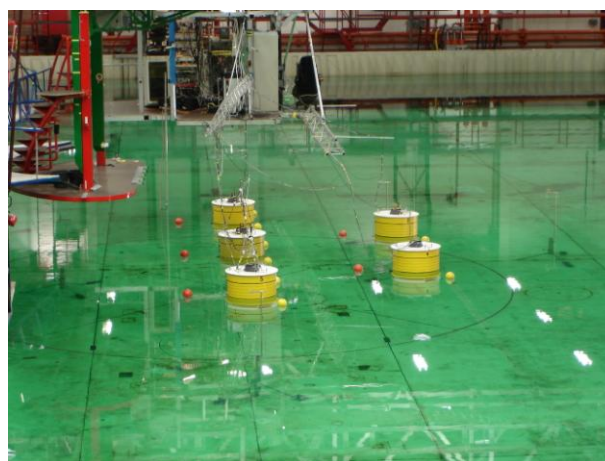
- Investigated direct control of wave energy converters using a direct drive linear generator. This pioneering work was among the first to explore direct drive linear electrical generators for wave energy driven by the mechanical complexity and low conversion efficiencies offered by hydraulic- and pneumatic-based systems. The work established that direct drive power take-off could be a viable alternative provided that a control scheme based on reaction force control was able to maximise energy extraction. Papers WS5.2, WS5.5 & WS5.23 refer. Paper WS5.2 is 10<sup>th</sup> most downloaded in the IET Renewable Power Generation journal.
- Investigated fault mechanisms in generators and power converters in collaboration with NCKU in Taiwan and the University of Technology Sydney. There is little data on component reliability for wave and tidal generators. This work increased understanding of the potential component failure modes and informed design for reliability. In addition control methods were investigated to mitigate the impact of such faults, as referred to in papers WS5.31 and WS5.35.
- Developed a novel Permanent Magnet Generator C-GEN for direct drive applications. Two patents have been filed per Patents 1&2.
- Attracted Converteam to establish an Advanced Technology Group at Edinburgh to work on power electronics and electrical machines for renewable energy.
- Formed spin out company NGenTec to develop this technology and successfully raised £4m from VCs, industrial investment, and a grant from DECC.



## WS6 Moorings and positioning

WS6 explored the influence of mooring design and performance on the individual and multiple responses within arrays of wave converters simultaneously subjected to wave and tidal currents. This involved physical model tests and scale prototype tests in Strangford Lough. WS6 staff:-

- Won consequent funds from EU Hydralab to support access to the Marintek Ocean Basin in Trondheim to test an array of 1:20 scale heaving moored buoys with power absorption - this was the first array test of its type in the world. These tests showed that: currents acting orthogonal to the wave direction had limited influence on device responses; power capture could be enhanced by array configuration; severe resonant roll responses can be excited in regular waves – these interactions were not observed in irregular or short-crested waves; short-crested seas can lead to increased mooring forces; mooring loadings in an array can exceed those of single devices; the motion responses and mooring forces for a single device broadly correspond with predictions of a commercial software package. The implications of these findings are that devices intended to be moored in arrays should be tested in arrays in a wide range of conditions spanning both power recovery and survival conditions, as discussed in papers WS6.3, WS6.6, WS6.8 and WS6.9.
- Completed basin testing on mooring damping and stiffness with University of Exeter. Tests on different mooring configurations have quantified that relatively large surface buoys are effective shock absorbers which limit the peak loads in the mooring system. This implies that mooring design should consider the total behaviour of each mooring leg as well as individual components and that sufficiently robust shock absorbing components should be included in the overall design to limit mooring loads in survival conditions. Paper WS6.11 refers.



- Completed a simulation study of the interaction between mooring ground chains and the sea bed. This analysis has quantified the influence of tidal range and wave conditions on the sea-bed interactions. Paper WS6.10 refers to how moorings in particular can scour the sea bed.
- Developed a novel inertial motion monitoring methods for field measurements of moored devices.
- Designed, constructed and deployed a moored wave energy device in Strangford Lough including measurement of motions and mooring forces. Unlike previous tests in wave basins, these open-water trials resulted in mooring force measurements combining wave and current forcing with strong tidal influences. The force time-series are highly non-stationary and nonlinear necessitating the development of non-standard analysis methods in both time and frequency domain.

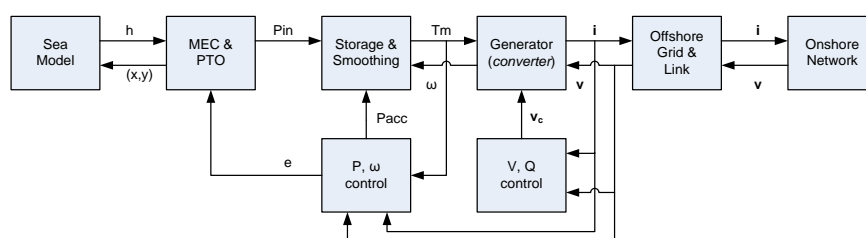


- Contributed mooring load cells and inertial motion measurement device to the EVOPOD tidal energy project (Oceanflow Energy) trials in Strangford Narrows.
- Designed, constructed and deployed a mooring test buoy in Falmouth bay.
- Won consequent funding from TSB, in collaboration with Ocean Power technology, to support development of the PB500; and with Fred Olsen to develop the FO device for installation at Wave Hub; and with Bauer, Voith Siemens and Mojo maritime to develop marine installation methods.

## WS7 Advanced control of devices and network integration

WS7 has developed a real-time wave to wire model of an array of moored wave devices, each with power take-offs and control systems, that is connected to a configurable electricity network. It has:-

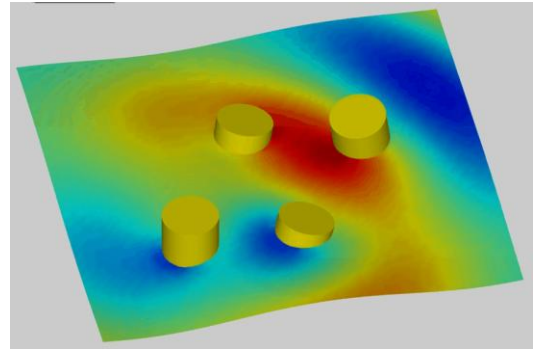
- Extended the understanding of simple device control and response. Paper WS7.7 extends the theory on capture width of a linear WEC and shows it to depend on two properties: the spectral power fraction (a property introduced in this paper), which depends entirely on the sea state, and the monochromatic capture width, which is determined by the geometry of the WEC and the chosen power take off (PTO) coefficients. For the first time capture width was shown to be a measure of how well these two properties coincide. The paper considered the effects of PTO control on the capture width and distinguished between this and geometry control. It listed the assumptions made in the formulation of capture width and highlighted the limitations of capture width as a design tool for estimating annual power capture of a wave device.
- Developed array planning tools that can increase power smoothing and network integration. Paper WS7.4 describes the development of a generic, time domain, wave-to-wire model used to explore the effects of: increased device numbers, array size and physical positioning and adjustment of control



parameters. The three-dimensional wave field was modelled as non-stationary, with statistical

characteristics that are extracted from measured wave elevation time series to simulate increasingly realistic sea conditions. Each heaving buoy has high-pressure oil power take off with on-board energy storage, driving Doubly Fed Induction Generators. The results obtained show the overall effects of storage on real power production, and the effects of imaginary power control on network voltage profile. The opportunities for increased yield and power quality through array layout, improved control and network integration are identified and discussed. WS7.12 goes on to explore the operation of wave arrays using four different controllers used to improve voltage quality (constant voltage, constant power factor, automatic voltage:power factor and fuzzy logic). The responses under these control algorithms were tested in highly, moderately and weakly energetic seas.

- Built and integrated a numerical wave to wire array model in with applied state space techniques to embodying refraction and diffraction between any number of any device forms in any geometry – inside the loop control time steps of the models. WS7.13 describes a wave-to-wire model of a large array of wave energy converters and demonstrates the overall effects of storage on real power production and imaginary power control on network voltage profile. Opportunities for improved network integration were identified and discussed.
- Developed novel linear and non-linear control algorithms to control device motion for optimal energy capture. Papers WS7.5, WS7.6 and WS7.14 continue to develop techniques for the advanced control of power take off in a point absorber wave energy converter. The motion of the hull is simulated using non-linear techniques under hydrodynamic excitation and mechanical-hydraulic reaction forces. The set point in the power take off control system is adjusted continuously to optimise power capture according to device response. A Proportional-Integral-Plus (PIP) methodology has been developed and applied to the PTO controller. However, PIP controllers are demonstrated not to fully-account for the interconnected system variables. The work has continued to develop new 'feed-forward' and 'state-dependent' forms of PIP control, in which the actuator piston velocity is appended to a non-minimal state space representation of the system. This has been shown to considerably improve response, set-point tracking and controllability.



## WS8 Reliability

WS8 has established an effective method to quantify the reliability of marine energy converters even with the scarcity of industry-specific component failure rates and environmental data. It has:

- Developed functional block diagrams and assessed the reliability of various tidal devices by interpretation of limited failure data from the wind sector and other sources, as discussed in papers WS8.8 and WS8.17.
- Developed a method for quantifying failure rates of mechanical components in marine energy converters using generic failure data and new information from deployed devices, as referred to in papers WS8.10 and WS8.11. This establishes a tool for systematic and consistent comparative reliability assessment of tidal current devices with different architectures to provide information that can improve the reliability of existing devices and develop new devices with higher reliability. It also provides a means to carry out preliminary reliability assessment of a device at the design stage and then constantly update it after deployment, as referred to in papers WS8.2 and WS8.7.
- Developed models for reliability analysis of structural components (e.g., blades, mooring systems) of marine energy converters, with results that can be used either for the direct reliability assessment of such devices, or for the calibration of partial safety factors in their design; papers WS8.10 and WS8.13 refer. The work in papers WS8.3, WS8.4 and WS8.5 implements the 'influence' (or 'multiplying') factors method to evaluate failure rates of mechanical components in tidal current turbines. It uses generic failure data presented by the basic failure rate which is multiplied by the so-called 'influence' factors to account for actual operational and environmental conditions of the component. The work carried out within the project creates the opportunity to apply the general method to mechanical components (e.g. bearings, seals, shaft) of tidal turbines so that the failure rates predicted can be used for the reliability assessment of the turbines.



- Begun to define maintenance regimes for tidal current technologies, contributing to the development of efficient maintenance policies for arrays of such devices.
- Established a test rig for components of wave energy converters. Accelerated life testing of the components is now underway to provide data about their failures and contribute to the reliability assessment of such devices, as referred to in papers WS8.6, WS8.7, WS8.9 and WS8.15.

## **WS9 Economic analysis of variability and penetration**

WS9 examined various aspects of the economics of marine energy, including the economic effects associated with increased marine energy penetration, recognising the significance of the variability of the resource. In this workstream Phase 2 staff have:

- Delivered economic analysis, funded by the Scottish Government, that informed the Scottish Climate Change Bill using energy-economy-environment computable general equilibrium models (CGEs). Paper WS9.3 reported the first application of CGE modelling to the development of the wave energy sector. The paper analysed the likely economic and environmental impacts that the installation of 3GW of marine energy capacity, required to meet the Scottish Government's renewable energy targets, would have on Scotland. The paper showed that the development of a marine energy sector, with strong encouragement to establish an indigenous supply chain, could have substantial effects on GDP, employment and the environment. It also demonstrated the potential for substantial "legacy" effects that persist well beyond the life of the devices.
- Shown that the levelised costs of tidal current technology are competitive with offshore wind. Paper WS9.13 calculated the private levelised costs of one wave and one tidal energy technology for UK electricity generation and compared them with ten other electricity generation technologies whose costs were identified by the UK Government. Sensitivity analysis showed how these relative private levelised costs calculations are affected by variations in key parameters, specifically the assumed capital costs, fuel costs and discount rate.
- Analysed the impact of banded ROCs for marine generation. Paper WS9.13 also considered the impact of the introduction of technology-differentiated financial support for renewable energy on the cost competitiveness of wave and tidal power in Scotland and the UK. The findings suggest that the Scottish Government's ROC bandings for marine renewables make tidal current technologies highly competitive with offshore wind, but that the levelised costs of wave energy remain high. It also suggests that portfolio analysis, rather than standalone levelised costs calculations, is a more comprehensive method for assessing the contributions of marine energies to the UK electricity portfolio.
- Shown that wave and tidal technologies could offer 'portfolio benefits' in the form of reduced electricity portfolio risks at no additional cost relative to a range of 2020 scenarios for UK and Scottish electricity generation portfolios. Levelised cost calculations are an important indicator of the economic viability of energy technologies, but they omit a potentially important contribution that renewables can make to a broader electricity generation portfolio – that of reducing the variability of portfolio costs due to the absence of correlation with fuel prices. Paper WS9.12 is the first systematic application of portfolio theory incorporating wave and tidal technologies. It examines likely drivers of the generation portfolio out to 2020 and assesses a range of scenarios against the mean-variance efficient portfolios that the analysis identifies. Electricity costs were shown to be higher with greater renewable energy content, but the paper also established that wave and tidal technologies can reduce portfolio risks without increasing cost.
- Developed and applied new methods for analysing the economic (aggregate and sectoral GDP and employment effects) and environmental impacts of renewable energy developments. Paper WS9.9 developed a social accounting matrix approach and reported work that demonstrated the potentially crucial influence of community benefits and co-ownership on the scale of the local economic development impacts of renewables. This was illustrated using the example of the Viking windfarm, but the method is transferable to coastal communities experiencing marine developments. In other applications CGE modelling took full account of induced supply side impacts on the host economy with applications to wave and tidal current technologies in the UK and Scotland.
- Conducted cost benefit analyses for illustrative marine energy installations, and demonstrated the potential benefits of tidal energy over coal, gas and onshore wind energy plants from a welfare perspective. Phase 2 staff calculated the costs and benefits of illustrative wave and tidal energy developments, incorporating monetary values for both private and social costs and benefits, and

compared the net benefit of wave and tidal energy projects to alternative wind, gas and coal power installations. The analysis found potential net benefits of tidal energy over coal and gas plants due partly to the existence of positive externalities associated with emissions savings, and net benefits over onshore wind power are identified due partly to the avoidance of ‘visual disamenities’ associated with wind turbines.

- Developed a new CGE framework for analysing the importance of capital subsidies and learning effects in helping to achieve the Scottish Government’s 2020 targets for marine renewable energy generation. This modelling framework represents a significant contribution to the literature, being the first example of a forward-looking CGE model for Scotland, and the first attempt to incorporate an explicitly disaggregated marine electricity sector. This enabled simulations that deepened understanding of what measures could conceivably allow the Government to achieve its (implied) target for marine renewables.

## WS10 Ecological Consequences of Tidal & Wave Energy Conversion

WS10 aimed to establish the sensitivity of marine environments to the artificial extraction of energy from tidal currents and waves, to enable the quantification of the risk from device developments and for subsequent mitigation, monitoring or avoidance strategies to be evaluated. It has:

- Completed a 5 year dataset of seal, porpoise and seabird activity around SeaGen in the Strangford Narrows and made detailed video surveys of benthic communities at four locations downstream of turbine
- Shown that energy extraction and the presence of SeaGen has had no significant biological impact to date on the benthos or on seal, porpoise and seabird activities adjacent to Seagen. Suites of observational data on seal, porpoise and seabird activities and the benthic community structure have been obtained over a 5 year period adjacent to the turbine. Two new grants have been obtained to implement a generic study of the relationship between current velocity and benthic community structure and to investigate, using a turbulence resolving model, the small scale relationship between local patterns of velocity fluctuations and benthic structure.
- Obtained a detailed year-long dataset on a range of physical variables and biological parameters related to the population responses of subtidal and intertidal kelp beds to a range of hydrodynamic environments. A core programme component has focussed on the growth response of field populations of the subtidal kelp, *Laminaria hyperborea*, to differences in the incident wave field. The investigation has measured a wide range of biological and physical parameters at wave exposed and sheltered sites in the field, emphasising the derivation of physical parameters as routinely obtained by engineers, of direct relevance to the biology. Results suggest minimal differences in the physiological properties of the plants from the two sites, but significant differences in the hydrodynamic parameters between sites. Another component of the research focussed on the growth response of an intertidal kelp, *L. digitata*, to gradients in waves and currents climate. The investigation also measured a wide range of biological and physical parameters in the field over a year. Results indicate an inverse relationship between growth rate and hydrodynamic activity, with the highest growth rates occurring in areas with the slowest currents.
- A series of laboratory experiments in winter and summer has been carried out on juvenile plants of the kelp *L. digitata* to compare the influence of oscillating versus unidirectional flow on growth and nutrient uptake rates. There were no significant differences in growth rate between the two treatments in either winter or summer. There was no significant effect of treatment on nutrient uptake rate, however results suggest that increased water velocity increased nutrient uptake in low nitrogen summer periods but not in winter when nitrogen is found in high concentrations.



- Made a suite of direct measurements of incident wave energy absorbed by kelp beds. An ongoing suite of measurements is being made to quantify the absorption of wave energy by beds of the kelp, *Laminaria hyperborea*. The programme relies on close integration of detailed physical measurements and the biology. Kelp beds are ecologically important and are extensively distributed down to 15-20 m and are thought to be significant absorbers of wave energy. There is a possibility that the structure of these beds will be affected by the establishment of inshore wave energy devices.
- Recorded a complete littoral baseline for west coast of Orkney Mainland, including extensive cliff areas never previously accessed. Baselines for future biological monitoring have been established using a new methodology of paired species, enabling in future any impacts of energy extraction to be differentiated from those of climate change. Sentinel species, likely to be sensitive to energy extraction have been identified.
- Information on the rare seaweed *Fucus distichus* and its distribution in Orkney has been improved, allowing identification of environmental features associated with its occurrence and hence improved ability to predict its response to future changes. The characterisation of the sublittoral from near-shore to 50m depth (using ROV and drop frame), following consultation with marine energy developers in selecting target areas, is nearing completion. Software has been developed for quantification of marine biotopes based on digital stills photography. Further development of photographic image analysis software for automated processing of data on littoral biotopes is now being considered.
- Characterised turbulent flow in the EMEC Fall of Warness test site and published the effects of this on distribution of species. A turbine collision detection system, developed by SuperGen staff has been trialed and is now being used by a device developer on the SRT 250 prototype tidal turbine during its tests at the Fall of Warness at EMEC. It will make significant measurements to provide robust data on the perceived threat to sea-life.
- Developed and field tested the Terabuoy which provides proxy quantitative measures of shoreline energy exposure and provided an 18 month dataset of baseline measurements recorded at two locations on west coast of Orkney Mainland. It is now progressing to commercialisation. Similarly the Sonobuoy, developed for underwater noise measurement in wave and tidal current environments, has now been used by Voith and Scotrenewables for noise surveys in the Fall of Warness. The knowledge gained during this work has been used in the development of a study commissioned by SNIFFER (Scotland and Northern Ireland Forum For Environmental Research).



Much of the output from WS10 is based on analysis of data collected over long periods of time. The publications profile WS10.1 to WS10.20 reflects this, with many important findings still in preparation for submission.

### 3 Doctoral Training Programme

The Doctoral Training Programme continues and will train over 30 PhD students across the core and affiliate Universities, including six students funded by Highlands and Islands Enterprise and eight DTA students. Many have completed their research, gained their PhDs and taken employment in the sector or in partner universities. Others starting later are finalising and nearing submission.



The DTP workshops below were attended by all SuperGen students, and many more studying marine energy at other universities in the UK or around the world. Many of the workshops were jointly delivered by SuperGen academics and industry partners.

Feb 2008	Wave Hydrodynamics	Edinburgh
Jun 2008	Marine Ecology and Field Work	Orkney
Sep 2008	Economics	Glasgow
Feb 2009	Electrical Networks, Connection and Conditioning	Edinburgh
Jun 2009	Tidal Hydrodynamics	Belfast
Sep 2009	Electrical Machines	Edinburgh
Feb 2010	Control	Lancaster
Jun 2010	Moorings and Fixings	Exeter

The students, their area of study, and status are listed below.

**Sarah Caraher:** ‘*Bearings for Linear Direct Drive Generators*’ University of Edinburgh – completed; Current place of work: Open Hydro.

**Eoghan Maguire:** ‘*Numerical modelling of Absorbing Wave-makers*’; University of Edinburgh – completed; Current place of work: Vattenfal.

**Jorge Lucas:** ‘*Dynamics of a Cylinder with an Off-Centered Axis of Rotation as a Wave Energy Converter*’; University of Edinburgh – completed; Current place of work – GL Garrad Hassan.

**Remy Pascal:** ‘*Quantification of the influence of directional sea state parameters over the performances of wave energy converters*’; University of Edinburgh – completed; Current place of work: University of Edinburgh.

**Anup Nambiar:** ‘*Coordinated control and network integration of wave power farms*’; University of Edinburgh – finalising.

**Aby Sankaran Iyer:** ‘*Methodologies for Evaluating Tidal Potential in UK*’; University of Edinburgh – finalising.

**Laura Finlay:** ‘*Numerical modelling of tidal resonance in response to the construction of a tidal barrage*’; University of Edinburgh – finalising; Current place of work: University of Edinburgh.

**Richard Crozier:** ‘*Design optimisation of linear electrical generators*’; University of Edinburgh – in progress; Current place of work: University of Edinburgh.

**Sam Euridge:** ‘*Wave Forecasting for Short-term Power Prediction*’; University of Edinburgh – in progress.

**Mairéad Atcheson:** ‘*Investigating the Hydrodynamic Performance of a Tidal Turbine*’; Queens University Belfast – in progress.

**Damien Scullion:** ‘*Morphology and Ecology of the Kelp *Laminaria digitata* in Relation to the Hydrodynamic Environment*’; Queens University Belfast – finalising; Current place of work: Queen's University Marine Laboratory, Portaferry.

**Adam Bedford:** *'Strength in Flexibility - Research in Innovative Flexible Permanent Magnet Generator Designs'*; Lancaster University – completed; Current place of work: University of Central Lancashire.

**Andrew Good:** *'Analysis of the near wake of a horizontal axis tidal turbine'*; Queens University Belfast – in progress.

**Philip Cross:** *'Continuous-time PIP control of marine energy converters'*; Lancaster University. –finalising.

**Jon Winchester:** *'A numerical investigation into torque ripple and power in vertical axis tidal turbines'*; Lancaster University – completed.

**Philip Thies:** *'Reliability of marine energy converters'*; University of Exeter – completed; Current place of work: University of Exeter.

**Andrew Vickers:** *'Numerical implementation of experimentally derived damping properties of mooring lines for Wave Energy Converters'*; University of Exeter – completed.

**Michelle Gilmartin:** *'Modelling the potential economic impact of developments in the UK tidal energy sector'*; University of Strathclyde – completed; Current place of work: University of Strathclyde.

**Matthew Winning:** *'Economics of climate change, carbon policy and renewable energy'*; University of Strathclyde – finalising.

**Sam Rose:** *'Characterising downstream wake development and propagation in horizontal axis tidal turbines'*; University of Strathclyde – finalising.

**Bob Beharie:** *'Exploring Links between Wave Regime Changes and Biotic Assemblages'*; Heriot-Watt University – in progress.

**Patricia Okorie:** *'Scale Effects in Tidal Current Devices'*; The Robert Gordon University – finalising.

**Armando Alexandre:** *'Wave energy strings for electricity production and coastal protection'*; University of Manchester – finalising.

**Matthew Harrison:** *'CFD Techniques for Modelling Wake Effects in Tidal Turbine Arrays'*; Southampton University – finalising;

**Tatania Delorm:** *'Prediction of the Reliability of Tidal Stream Devices Using Surrogate Data'*; Durham University – in progress.

**Matthew Easton:** *'An integrated modelling framework for Environmental Impact Assessment of Large-Scale Tidal Arrays'*; Environmental Research Institute, University of the Highlands and Islands – in progress.

**Andrew Commin:** *'Renewable energy in the Pentland Firth'*; Environmental Research Institute, University of the Highlands and Islands – in progress.

**Astrid Harendza:** *'Ecological impacts associated with renewable energy devices in extreme marine environments'*; Environmental Research Institute, University of the Highlands and Islands – in progress.

**Karen Alexander:** *'The impacts of offshore power: mitigation through habitat provision'* Scottish Association for Marine Science UHI – in progress.

**Adrian Macleod:** *'The impacts of marine renewable energy structures on the invasion of biofouling non-native species'*; Scottish Association for Marine Science UHI – in progress.

**Raeanne Miller:** *'Offshore marine renewable energy structures as artificial islands: implications for dispersal, population connectivity and biogeography of coastal species'*; Scottish Association for Marine Science UHI – in progress.

Copies of the theses are, or will be, available from the universities.

## 4 Dissemination, Engagement and International Articulation

### 4.1 Dissemination of Output

The papers listed by workstream and alphabetically in Appendices 2&3 have disseminated results.

### 4.2 Industry Engagement and Knowledge Exchange

Industry engagement and knowledge exchange has been building steadily. The Research Advisory Forum includes representatives from: Pelamis Wave Power, Ocean Power Technology, Marine Current Turbines, Open Hydro, Scottish Power, Scottish & Southern Energy, E-On, NPower, EdF, The Carbon Trust, ETI, EMEC, NaREC, The Crown Estates and Scottish Natural Heritage.

There have been a number of collaborative ventures established in Phase 2, and many others during its programme, supported by TSB, ETI, Carbon Trust and Regional Development Agencies to connect effort of SuperGen staff with industry colleagues in Marine Current Turbines, Aquamarine, Rolls Royce, GL Garrad Hassan, Black and Veatch, Nortek, ORCINA, Edinburgh Designs, Measurand Canada, Fountain Design Ltd, Wavegen and Scotrenewables Ltd.

Converteam have established their Advanced Technology Group at Edinburgh to develop high voltage DC power electronic control and novel generators. Under a 5 year Framework Agreement with EdF R&D, Phase 2 staff are implementing new free surface and Cartesian cut-cell models for the open source "Code\_SATURNE" flow solver.

The spinout company NGenTech attracted investment to establish manufacture of the patented C-Gen technology and increase the rating of this novel direct-drive slow speed permanent magnet generator for wind and marine generation.

### 4.3 Engagement with Policy, Standards and Regulation

Staff have led or contributed to the following to engage with policy, standards and regulation formation.

- Scottish Executive (2006); "Academic Study: Matching Renewable Electricity Generation with Demand: Full Report". Produced by University of Edinburgh by Boehme, T., Taylor, J., Wallace, A.R. and Bialek, J. ISBN 0 7559 502. <http://www.scotland.gov.uk/Publications/2006/04/24110728/0>.
- Smith, G.H. & Taylor, J. (2007): "Preliminary Wave Energy Device Performance Protocol". Research commissioned by the Department of Trade and Industry, [http://www.decc.gov.uk/assets/decc/what%20we%20do/lc\\_uk/ic\\_business/env\\_trans\\_fund/marine\\_fund/file38989.pdf](http://www.decc.gov.uk/assets/decc/what%20we%20do/lc_uk/ic_business/env_trans_fund/marine_fund/file38989.pdf)
- Couch S.J. & Jeffrey, H.F. (2007): "Preliminary Tidal Current Energy Device Performance Protocol". Research commissioned by the Department of Trade and Industry, [http://www.decc.gov.uk/assets/decc/what%20we%20do/lc\\_uk/ic\\_business/env\\_trans\\_fund/marine\\_fund/file38991.pdf](http://www.decc.gov.uk/assets/decc/what%20we%20do/lc_uk/ic_business/env_trans_fund/marine_fund/file38991.pdf)

Both the above documents have also been adopted by government and submitted as UK input to the IEA-OES see <http://www.iea-oceans.org/publications.asp?id=8> - report T02 3.1 and T02 3.2.

- Carbon Trust (2004): "Phase I UK Tidal Stream Energy Resource Assessment".
- Carbon Trust (2005): "Phase II UK Tidal Stream Energy Resource Assessment". <http://www.carbontrust.co.uk/SiteCollectionDocuments/Various/Emerging%20technologies/Technology%20Directory/Marine/Other%20topics/PhaseIITidalStreamResourceReport.pdf>

Both of these Carbon Trust reports were prepared by Black & Veatch, with SuperGen staff delivering the underpinning scientific methodologies. They have very recently developed the methodology that has been used by Black & Veatch to reappraise the UK tidal current resource.

- Sustainable Development Commission (2007); "Tidal Power in the UK: Research Report 4 - Severn non-barrage options". An evidence-based report by AEA Energy & Environment for the Sustainable Development Commission. [http://www.sd-commission.org.uk/publications/downloads/TidalPowerUK4-Severn\\_non-barrage\\_options.pdf](http://www.sd-commission.org.uk/publications/downloads/TidalPowerUK4-Severn_non-barrage_options.pdf).
- Sustainable Development Commission (2007); "Tidal Power in the UK: Research Report 5 - UK Case Studies". An evidence-based report by AEA Energy & Environment for the SDC [http://www.sd-commission.org.uk/publications/downloads/TidalPowerUK5-UK\\_case\\_studies.pdf](http://www.sd-commission.org.uk/publications/downloads/TidalPowerUK5-UK_case_studies.pdf).

SuperGen staff prepared the above reports which were also used (along with the other 3 commissioned

reports) as inputs to the SDC "Turning the Tide" document.

SuperGen staff lead or contribute to four of six of the EU teams that are delivering

- IEC Standard TC114 Marine Energy – Wave and Tidal Energy Converters  
[http://www.iec.ch/dyn/www/f?p=102:7:0:::::FSP\\_ORG\\_ID:1316](http://www.iec.ch/dyn/www/f?p=102:7:0:::::FSP_ORG_ID:1316)

SuperGen staff have produced or contributed to the production of the following:

- UK Energy Research Centre Marine Energy Roadmap (2007)  
[http://ukerc.rl.ac.uk/Roadmaps/Marine/Tech\\_roadmap\\_summary%20HJMWM.pdf](http://ukerc.rl.ac.uk/Roadmaps/Marine/Tech_roadmap_summary%20HJMWM.pdf)
- UK Energy Technologies Institute Marine Energy Roadmap (2010)  
[http://ukerc.rl.ac.uk/Roadmaps/Marine/ETI\\_UKERC\\_Roadmap\\_2010.pdf](http://ukerc.rl.ac.uk/Roadmaps/Marine/ETI_UKERC_Roadmap_2010.pdf)
- DECC UK Marine Action Plan  
[http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/uk\\_supply/energy\\_mix/renewable/explained/wave\\_tidal/funding/marine\\_action\\_/marine\\_action\\_.asp](http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/explained/wave_tidal/funding/marine_action_/marine_action_.asp)
- Scottish Government Roadmap for Marine Energy Development (2010)  
<http://www.scotland.gov.uk/Resource/Doc/281865/0085187.pdf>
- Oceans of energy: European Ocean Energy Roadmap 2010-2050  
<http://www.eu-oea.com/euea/files/ccLibraryFiles/Filename/000000000827/ocean%20vectorise%2010%20mai%202010.pdf>
- European Science Foundation: Marine Board Vision Document (2010)  
[http://www.esf.org/index.php?eID=tx\\_nawsecuredl&u=0&file=fileadmin/be\\_user/research\\_areas/marine/pdf/Publications/MB%20VD2\\_Marine%20Renewable%20Energy\\_web.pdf&t=1291724787&hash=2657c57acba5c496f4c7c9542102964e](http://www.esf.org/index.php?eID=tx_nawsecuredl&u=0&file=fileadmin/be_user/research_areas/marine/pdf/Publications/MB%20VD2_Marine%20Renewable%20Energy_web.pdf&t=1291724787&hash=2657c57acba5c496f4c7c9542102964e)
- The 2011 ORECCA European roadmap for offshore wind, wave and tidal power
- The IEA international Vision for Ocean Energy and represented DECC on the International Energy Agency implementing agreement for Ocean Energy .

#### 4.4 International Articulation

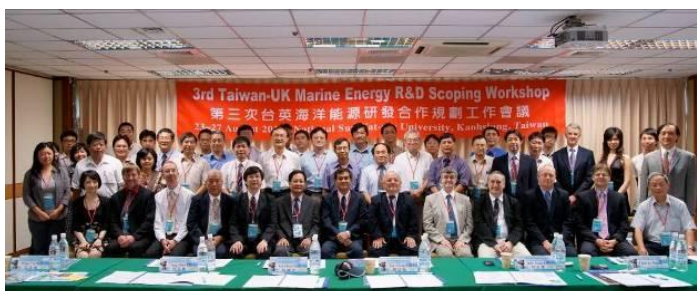
International articulation has continued to grow as follows.

**Europe:** There are many collaborative projects between SuperGen staff and colleagues across Europe, including EQUIMAR, MARINET, ORECCA, MARINA, ADORET, SNAPPER, BioMara and WaveTrain.

SuperGen staff established and now lead the European Energy Research Alliance in Marine for the UK, this is currently the only EERA discipline to be led by the UK (April 2010). It includes researchers from the University of Edinburgh (UK), Wave Energy Centre (Portugal), Tecnalia (Spain), HMRC (Ireland), SINTEF/MARINTEK (Norway), IFREMER (France), Fraunhofer IWES (Germany) and ENEA (Italy). UKERC member Henry Jeffrey, a senior researcher based at the University of Edinburgh will lead the project. The EERA programme supports the emerging marine renewable energy sector by producing coordinated and strategic underpinning research that will allow the sector to be incorporated in to the wider European energy strategy. Furthermore, it will assist the sector in achieving successful commercial deployments and growth. The EERA Joint Programme in Marine Renewable Energy focuses on six key themes: Resource; Devices and Technology; Deployment and Operations; Environmental Impact; Socio-economic Impact and Research Infrastructure, Education and Training.

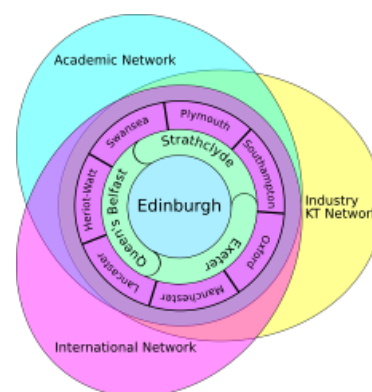
**USA and Canada:** Memoranda of Understanding and research collaborations are established with several universities including the University of Washington, Florida Atlantic and Oregon State and the New England Marine Renewable Energy Centre. Academics and research staff regularly work with US partners to facilitate events and scope marine hydrokinetic R&D programmes. There is extensive cooperation with Dalhousie University, OREG and FORCE in Canada.

**Asia:** There have been many outward and inward missions by SuperGen and Taiwan academics and industrialists, including a series of R&D scoping workshops. SuperGen staff now work on joint projects with colleagues in three Taiwan universities and host academic exchange visits. There are established collaborations with Chinese universities, with British Council funding student exchange with the Key State Marine Labs in Dalian.



## 5 SuperGen Marine Phase 3

In the third phase, the core consortium now consists of the University of Edinburgh, the University of Strathclyde, Queen's University Belfast and the University of Exeter. The consortium includes associate Universities of Plymouth, Heriot-Watt, Lancaster, Manchester, Swansea, Oxford and Southampton. Additional universities will join depending on their funding status from such initiatives as the EPSRC Marine Energy Grand Challenges programme.



### 5.1 Rationale and Vision

There are agreed and adopted R&D, technology and deployment roadmaps, produced and maintained by staff of SuperGen Phases 1&2. Based on these roadmaps the aims of the research, network and capacity building of the third phase have evolved to support the sector at and beyond its current stage of development. The aims of the consortium are

- *To conduct world-class fundamental and applied research that assists the marine energy sector in the UK to reliably and dependably accelerate deployment rates and ensure sustained growth in generating capacity to meet the 2020 targets.*
- *To expand and effectively operate an inclusive network of academic researchers, industry partners and international collaborators.*
- *To continue to provide the highest quality of doctoral training and knowledge transfer in partnership with industry to build intellectual and human capacity for the sector.*

SuperGen Phase 3 has established and will operate the **UK Centre for Marine Energy Research**.

### 5.2 Structure and Operation

The Centre Management Team is:

Wallace	PI, Executive Director, Financial Management
Bryden	Research Director, with responsibility for technology and R&D foresighting
Ingram	Doctoral Training Manager, with responsibility for EU liaison
Jeffrey	Marine Network Manager, industrial liaison, and road-mapping
Whittaker	Natural Environment & Deployment Infrastructure, Ireland and Wales liaison
Johnstone	Knowledge Exchange, Economic Interface, Scotland liaison
Smith	Supply Chain, Policy Interface, England and SW liaison

The Marine Energy Network is open-access and includes academic, industry and international partners, including continuation of the Research Advisory Forum (RAF) to provide formal feedback, input and steerage. The international network will develop and formalise extant relationships with European countries and USA and Asia.

The industry network includes existing collaborators and is open to all interested and committed device and component manufacturers, developers, utilities, agencies, regulatory bodies and government departments. It works in close collaboration with the Energy Generation and Supply Knowledge Transfer Network.

The academic network includes staff with research interests in or related to marine energy from university and HE colleges that are not already core or associate members. The international network includes all interested and committed researchers from outside the UK that are in a position to engage with the work of the Centre. There are identified academics or industry partners in USA, Canada, Taiwan, China, Japan, Hong Kong, Korea, France, Spain, Germany, Ireland, Norway and Portugal.

Doctoral Training continues across core and associate universities and industry partners in a Programme coordinated by the management team operate in conjunction with the Industrial Doctoral Centre in Offshore Renewable Energy (IDCORE) operated by the Centre. Additionally, as in Phase 2, eight residential training schools are planned, each covering a distinct aspect of marine energy. Coordinated by the DTP manager, courses will be delivered by experts drawn from the academic, industrial and international parts of the network. These Schools will be open to any other UK doctoral students in marine energy and their supervisors, additionally to all network members. CPD credits will be awarded to participants.



### **5.3 Technology Research Strategy**

The marine renewable industry has developed road maps, including those published by UKERC. These have highlighted issues posing significant challenges that may hinder or delay the development of an economically viable industry, including: predictability; manufacturability; installability; operability; survivability; reliability and affordability. These all require complementary development of new industrial applications and underpinning research, where there are gaps in the necessary knowledge. The following initial themes, as examples, follow a gap analysis conducted over the roadmaps and developer issues against currently funded research programmes. This dynamic mapping process will continue throughout the project, building on an evolving appreciation of the issues and needs, fed back through the industrial network members.

#### ***Array Planning***

Understanding the nature of the interactions between waves and current on the behaviour of energy technologies remains a significant scientific and technical challenge. Enhanced understanding of hydrodynamic processes will improve: prediction of system behaviour; the safe and effective installation of devices; the survival of devices once they are installed and the quantification of the long term reliability of systems by improved understanding of fatigue resulting from improved appreciation of long term statistics of forces and strains.

#### ***Turbulence***

Turbulence has highly significant impacts on marine energy systems. Eddies have been identified with physical sizes of the same order as prototype tidal rotors, which will have influence on power quality, control and fatigue. Similarly eddies shed from mooring structures will have influence on long-term fatigue. A better understanding of fatigue loading will lead to significant improvements in *reliability*, and reduce the need for over-design leading to improved *affordability*.

#### ***Power Take Off Development***

PTO systems in wave energy devices in particular are exposed to stochastic reciprocating loads and must respond appropriately. There are still design challenges such as: the undesirability of ‘end stops’, and the need for weight and cost reduction, which need considered. Furthermore, there are only three feasible types of secondary power conversion: turbine (both air and water), hydraulic motors and direct electrical induction. Water turbines, hydraulic motors and direct electromagnetic induction machines are not normally designed for the stochastic reciprocating input from wave power. Maintaining efficiency while reducing weight and cost will be explored through integrated design of novel direct-drive PTOs.

#### ***Reliability***

Many components in devices are being asked to operate well away from their design conditions, for example hydraulic rams or linear bearings will rarely move over their entire range but will make millions of smaller oscillatory motions during their life. The fatigue life of components is often very rapidly exceeded by operating with 10 second loading cycles with a high dynamic range. These issues are critical for driving down costs by improving *manufacturability*, *operability* and *maintainability* of devices and fundamental and applied research will develop novel solutions subjected to accelerated testing.

#### ***Mooring and Foundations***

In existing demonstration projects the mooring and foundation systems are specifically designed for each deployment site. As the sector expands, it is critical that more general fixing technologies are developed, and an important pre-cursor to this is to extend the previous work mapping resource against deployment constraints to include geotechnical information about the sea floor. An integrated GIS system will be established to allow developers to identify similar sea bed types at locations suited for the deployment of large scale farms, leading to reduced installation costs and greater reliability.

#### ***Environmental Impact***

Technology has an impact on the natural environment. This includes the physical effects on the wave and current conditions, with consequent influences on, for example, sedimentation. There is also the possibility of on-going impact on the indigenous flora and fauna which may range from immediate effects associated with possible collisions between marine mammals and marine structures or their components, such as tidal turbine blades to more subtle long-term changes of ambient ecosystems. The capacity developed in Phase 2 will continue to monitor and develop new technology for monitoring the ecosystem.

The research staff in Phase 3 will operate flexibly to establish pathways to solve these and other challenges identified across the sector, and to work in partnership with industry collaborators to raise additional funds and deliver the necessary research outcomes.

## Appendices

### Appendix 1 Staff and Students of SuperGen Phase 2

#### Academic and Admin Staff

Prof. A. R. Wallace – University of Edinburgh  
 Prof. I.G. Bryden – UoEd  
 Prof. D. M. Ingram - UoEd  
 Dr. M.A. Mueller - UoEd  
 Prof. T. Whittaker – Queens University Belfast  
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 Mr. B. T. Linfoot – Heriot-Watt University  
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 Prof. K. Swales - UoS  
 Dr. G. A. Allan - UoS  
 Mr. C. Johnstone - UoS  
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 Dr. L. Johannng – UoEx  
 Prof. P.K. Stansby – University of Manchester  
 Prof. A.S. Bahaj – University of Southampton  
 Dr. A. Owen – Robert Gordon University  
 Prof. P. Tavner – Durham University  
 Dr D. Woolf – University of Highlands& Islands  
 Dr. B. Wilson - UHI  
 Ms. Pauline Clark – UoE

#### Research Staff

Mr. Henry Jeffrey – UoE  
 Dr. S. Couch – UoE  
 Dr. G. Payne – UoE  
 Dr. D. Forehand – UoE  
 Dr. M. Topper – UoE  
 Dr. J. Shek - UoE  
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#### Research Staff - contd

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 Dr. A. Want – HWU  
 Dr. C. Iliev – HWU  
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#### Doctoral Students

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 Laura Finlay  
 Richard Crozier  
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 Damien Scullion  
 Adam Bedford  
 Andrew Good  
 Philip Cross  
 Jon Winchester  
 Philip Thies  
 Andrew Vickers  
 Michelle Gilmartin  
 Matthew Winning  
 Sam Rose  
 Bob Beharie  
 Patricia Okorie  
 Armando Alexandre  
 Matthew Harrison  
 Tatania Delorm  
 Matthew Easton  
 Andrew Commin  
 Astrid Harendza  
 Karen Alexander  
 Adrian Macleod  
 Raeanne Miller

## Appendix 2 Publications by workstream

### WORKSTREAM 1 - Numerical and physical convergence

- WS1.1 GAO, F., INGRAM, D. M., CAUSON, D. M. & MINGHAM, C. G.: “The development of a Cartesian cut cell method for incompressible viscous flows”, *International Journal for Numerical Methods in Fluids*, vol. 54, (2007), pp. 10331063.  
<http://onlinelibrary.wiley.com/doi/10.1002/flid.1409/pdf>

This paper describes the extension of the Cartesian cut cell method to applications involving unsteady incompressible viscous fluid flow. The underlying scheme is based on the solution of the full Navier–Stokes equations for a variable density fluid system using the artificial compressibility technique together with a Jameson-type dual time iteration. The computational domain encompasses two fluid regions and the interface between them is treated as a contact discontinuity in the density field, thereby eliminating the need for special free surface tracking procedures. The Cartesian cut cell technique is used for fitting the complex geometry of solid boundaries across a stationary background Cartesian grid which is located inside the computational domain. A time accurate solution is achieved by using an implicit dual-time iteration technique based on a slope-limited, high-order, Godunov-type scheme for the inviscid fluxes, while the viscous fluxes are estimated using central differencing. Validation of the new technique is by modelling the unsteady Couette flow and the Rayleigh–Taylor instability problems. Finally, a test case for wave run-up and overtopping over an impermeable sea dike is performed.

- WS1.2 OKORIE, P.O., & OWEN, A.: “Turbulence: Characteristics and its Implications in Tidal Current Energy Device Testing.” *OCEANS 2008, MTS/IEEE Proceeding*, Quebec City, Canada, 15-18 September 2008.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5151900&tag=1](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5151900&tag=1)

This review paper presents the differences between highly idealised case of isotropic, homogenous and stationary turbulence and how it deviate from real flows from observations made in a tidal estuary from past studies. The scale of turbulence within tidal current pervades scales larger than the energy containing scale of turbulence. Scales other than the Kolmogorov scale of turbulence observed from previous studies are reported and the principle of dimensional analysis as a traditional tool to assess the effect of scaling tidal current energy devices is introduced.

- WS1.3 INGRAM, D. M., VILLATE, J. L., ABONNEL, C. & JOHNSTONE, C.: “The development of protocols for equitable testing and evaluation in ocean energy - a three year strategy”, *International Journal of Fluid Machinery and Systems*, vol. 1, (2008), pp. 33–37. **Invited paper.**  
<http://www.ijfms.org/>

EquiMar (Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact) is one of the first round of energy projects under the European Commissions 7th Framework Programme (FP7). The three year EquiMar project aims to deliver a suite of protocols for the evaluation of both wave and tidal converters, harmonizing testing and evaluation procedures across the wide range of available devices, accelerating adoption through technology matching and improving the understanding of both environmental and economic impacts associated with the deployment of devices. The EquiMar protocols will cover site selection, initial design, scaling up of designs, the deployment of arrays and environmental impact assessment as well as economic issues. EquiMar will build on existing protocols, e.g. UK DTI Marine Renewables Development Fund (MRDF) protocols for wave and tidal energy, and engage with international standards setting activities, e.g. IEC TC114.

- WS1.4 WATANABE, Y., SARUWATARI, A. & INGRAM, D. M.: “Free-surface flows under impacting droplets”, *Journal of Computational Physics*, vol. 227, issue 4, (2008), pp. 2344–2365.  
<http://www.sciencedirect.com/science/article/pii/S0021999107004640>

A numerical method which fulfils the free-surface boundary conditions and extrapolates the fluid velocity into empty grid cells outside the fluid region on a fixed Cartesian grid system is presented. The complex, three-dimensional, vortex structures formed via surface/vortex interaction and induction between vortices

have been computed using the proposed technique implemented within a level-set method for both vertical and oblique droplet impacts in incompressible fluids. The present results have been validated through numerical tests which confirm zero tangential shear at the free-surface and comparisons with experimental observations of cavity and vortex ring formation underneath the impact location. In some cases, transitions from a concentric vortex ring to a fully three-dimensional vortex structure has been confirmed. Whilst the primary vortex ring is initiated at the highly curved contact surface between the droplet and receiving surface, azimuthal instabilities are manifested in the shear layer around the cavity crater developing after the vertical impact, resulting in axial counter-rotating vorticity between the cavity and descending vortex ring. Underlying mechanisms which induce local deformation of the free-surface, creating a so-called scar, due to the sub-surface vortices at the oblique impacts are also discussed.

WS1.5 PAYNE, G. S., TAYLOR, J. R. M., BRUCE, T. & PARKIN P.: “Assessment of boundary-element method for modelling a free-floating sloped wave energy device. Part 1: Numerical modelling”, *Ocean Engineering*, vol. 35, issue 3-4, (2008), pp. 333–341.  
<http://www.sciencedirect.com/science/article/pii/S0029801807002193>

The boundary-element method has been widely used as a design tool in the offshore and ship building industry for more than 30 years. Its application to wave energy conversion is, however, more recent. This paper deals with the numerical modelling of a free-floating sloped wave energy device. The power take-off mechanism of the device consists of an immersed tube with a piston sliding inside. The modelling is done using the boundary-element method package WAMIT. The model is first worked out for the case where the axis of the tube is vertical. It is then derived for the tube inclined and successfully verified against numerical benchmark data. A companion paper presents results of a detailed comparison with a physical model study.

WS1.6 PAYNE, G. S., TAYLOR, J. R. M., BRUCE, T. & PARKIN P.: “Assessment of boundary-element method for modelling a free-floating sloped wave energy device. Part 2: Experimental validation”, *Ocean Engineering*, vol. 35, issue 3-4, (2008), pp. 342–357  
<http://www.sciencedirect.com/science/article/pii/S0029801807002181>

The boundary-element method has been widely used as a design tool in the offshore and ship building industry for more than 30 years. Its application to wave energy conversion is, however, more recent. This is the second of two papers on a comparison of numerical and physical modelling of a free-floating sloped wave energy converter. In the first paper the numerical modelling formulation for the power take-off mechanism was derived using the boundary-element method package WAMIT. It was verified against numerical benchmark data. In this paper, the outcome of the modelling of the whole device is compared with experimental measurements obtained from model testing in a wave tank. The agreement is generally good.

WS1.7 ORTEGA, J. & SMITH, G. H.: “Empirical assay of the use of the Hilbert-Huang transform for the spectral analysis of storm waves”, *Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering (OMAE2008)*, June 15-20, 2008, Estoril, Portugal.  
<http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=ASMECP00200804819700041900001&idtype=cvips&gifs=yes>

The Hilbert-Huang Transform (HHT) was proposed by Huang et al. [2] as a method for the analysis of non-linear, non-stationary time series. This procedure requires the decomposition of the signal into intrinsic mode functions using a method called empirical mode decomposition. These functions represent the essential oscillatory modes contained in the original signal. Their characteristics ensure that a meaningful instantaneous frequency is obtained through the application of the Hilbert Transform. The Hilbert Transform is applied to each intrinsic mode function and the amplitude and instantaneous frequency for every time-step is computed. The resulting representation of the energy in terms of time and frequency is defined as the Hilbert Spectrum. In previous work [7] using the HHT for the analysis of storm waves it has been observed that the number of IMFs needed for the decomposition and the amount of energy associated to different IMFs differ from what has been observed for the analysis of waves under ‘normal’ sea conditions by other authors. In this work we explore in detail the effect that the sampling rate has in the empirical mode decomposition and in the Hilbert Spectrum for storm waves. The results show

that the amount of energy associated to different IMFs varies with the sampling rate and also that the number of IMFs needed for the empirical mode decomposition changes with record length.

WS1.8 SMITH, G. H., ASHTON, I. G. C. & EVANS, M. J.: “Spatial Variation of Wave Parameters at a Site Specific Scale”, *Proceedings of the International Conference on Ocean Energy*, Brest, France, October 2008. <http://www.icoe2008.com/en/>

This paper discusses aspects of the medium scale spatial variation in the characterisation of wave climate. There have been relatively few investigations of simultaneous measurement of sea states at spatial separations of the order of 1 km. However the authors feel that this is an area that deserves more consideration and this paper will hopefully provoke a discussion of why such scale variations are important. Firstly, there is increasing interest in estimating the downstream effect of array scale wave developments. Many of the studies to date have used modified wave propagation models such as SWAN or Mike21 and the question of the physical basis for using such models must be considered. One possible solution is to undertake physical measurements of absorption at an operational wave farm to determine the downstream effects of removing energy from the climate. Such physical measurements might provide the means to tune the output from conventional numerical models. Secondly, the spatial variations across a wave energy site will also influence the determination of the short term performance of WEC devices and indeed the aggregated short term output from a small farm. This paper discusses some of these issues, with some illustrating data and examines the problems of implementing any measurement and analysis program.

WS1.9 SMITH, G. H., BITTENCOURT, C. & INGRAM, D.: “EQUIMAR: The Development of Protocols for the Equitable Evaluation of Marine Energy Systems”, *Proceedings of the ASME 28th International Conference on Ocean, Offshore and Arctic Engineering*, Honolulu, Hawaii, 31 May 2009 - 05 Jun 2009. <http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=ASMECP00200904344400103700001&idtype=cvips&gifs=yes>

This paper describes a major collaborative project funded through the European Union which seeks to accelerate the adoption of ocean energy systems through providing a rational suite of protocols that will: (i) help to match technology and scale of deployment to site specific considerations; (ii) define acceptable methodologies to evaluate the environmental consequence of deployment; (iii) develop techniques for equitable comparison of the economic potential; for the deployment of small to medium arrays. EquiMar involves 23 European partners, including scientists, engineers, ecologists and developers. Funded through the European Commission 7<sup>th</sup> Framework Programme [1] (grant agreement 213380), this €5.5 million project aims to produce a suite of protocols that will enable a broad range of stakeholders to judge the variety of technologies in wave and tidal energy on a level playing field. The protocols will reflect the entire development cycle of a marine device: resource assessment and site selection; fundamental engineering design; scaling up and deployment; environmental impact and economic assessment. The project has now been running for 12 months. This paper reviews the intended work over the three year project, but focuses on the development of “high level” documents that will describe the aims and remit of the individual protocols. The high level protocols were conceived to meet two fundamental requirements. EquiMar is an ambitious project in terms of both scope and number of collaborators. There is a need to maintain consistency and clarity as each protocol/ guideline is developed. The high level protocols will serve as a template for the detailed specifications, clarifying content, identifying gaps and links within the overall work and finally will help to maintain focus on the final goals. Externally the high level documents will provide a mechanism for engagement of the many stakeholders. Early feedback on the direction and coverage of the protocols is fundamental to achieving, where practical, a consensus from the diverse ocean energy community. Based on the practices of an international Certifying Agency (DNV) it is intended that the protocols will be fit for guidance and incorporation into proposed international standards. This paper aims to increase dissemination and provoke comment from the International marine community in order that that the final documents will be fit for purpose by reflecting the considered opinion of as wide a body of relevant contributors as is possible, and act as a catalyst to help deliver the potential for marine renewable energy on the international stage.

WS1.10 FINLAY, L., COUCH, S. J. & INGRAM, D. M.: “Numerical modelling of the response of tidal resonance to the presence of a barrage”. *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/index.html>

A tidal energy barrage has been proposed for the Severn Estuary, UK. In order to predict the effect such a structure may have on the tidal resonance in the channel, a simple two dimensional model has been developed for a series of simulated estuaries, ranging from a simple box channel with a uniform flat bed to a simple wedge shaped channel with a solid barrier across, to a simulation of the Severn Estuary with topographic and bathymetric values. These models show amplitudes and phases of elevation and current flow for each model scenario. model outputs show that overall tidal resonance decreases with the construction of a barrier across a channel.

WS1.11 GRETTON, G. I., BRUCE, T. & INGRAM, D. M.: “Hydrodynamic modelling of a vertical axis tidal current turbine using CFD”. *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/index.html>

Results from a computational fluid dynamics (CFD) model of a vertical axis tidal current turbine are presented. This CFD model has been implemented in the commercial code CFX and is a Reynolds-averaged Navier-Stokes solution with the  $k-\omega$  SST turbulence model. The turbine simulated is a 15 kW small-scale prototype device being developed by Edinburgh Designs Ltd. with independently and continuously variable pitch blades.

A major focus of the present work is the thorough verification and validation of the numerical model. This is based on a series of progressively more complex simulations, beginning with fixed pitch hydrofoils (airfoils), progressing to oscillating pitch hydrofoils, and finishing with a complete time-dependent model of the turbine.

The paper concludes with a parametric study of turbine performance, comparing fixed pitch and variable pitch operation and a four-bladed variant of the turbine with the three-bladed baseline. It is found that variable pitch operation both increases the peak power coefficient and broadens the peak in the power coefficient versus tip speed ratio curve. An increase in the number of blades (maintaining solidity) leads to a slight drop in performance, commensurate with Reynolds number effects.

WS1.12 MAGUIRE, E. & INGRAM, D. M.: “Hydrodynamics and absorption efficiencies of wavemakers”. *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/index.html>

For most of the twentieth century naval hydrodynamics, and more recently, wave energy hydrodynamics have been limited to the realms of theory and physical experiments. Both of these methods of fluid flow analysis are constrained through scope, cost and size of facility. The advent of high speed digital computing has brought with it a new dimension for analysing fluid flows, that of numerical modelling. This paper aims to harness this progress in computing power and established commercial computational fluid dynamics (CFD) codes to create a numerical analogue to the physical test flumes that are in operation in many hydrodynamic labs. Using numerical wavemakers will allow for the use of different shaped wavemakers that would be otherwise impossible to implement in a physical waveflume, these nonconventional shapes will be investigated.

This paper presents the well established wavemaker theory. This is then adapted to obtain the hydrodynamic coefficients of added mass and damping for two novel shaped wavemakers. The different wavemaker geometries are compared on the basis of their theoretical wave absorption efficiencies at various tuned frequencies. Wavemaking simulations using ANSYS CFX are then presented and the results are discussed.

WS1.13 PAYNE, G. S., RICHON, J., INGRAM, D. M. & SPINNEKEN, J.: “Development and preliminary assessment of an optical wave gauge”. *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/index.html>

A description and preliminary results are presented for a non-intrusive optical wave gauge based on the principle of optical triangulation. In the proposed implementation, a LASER source beaming vertically downwards generates a spot of scattered light at the water surface. The spot is imaged by an off-axis video camera, and instantaneous wave height measurements are obtained by processing of the spot images. The spot position on the image is then transformed into a height value using a polynomial best-fit function established by an initial calibration. The gauge geometry is set to give a measurement range of 300mm. The calibration method and apparatus are described. A detailed statistical analysis of the calibration results is presented both for the optical wave gauge and for a conductivity wave gauge used as a comparison. Dynamic measurements for regular waves of 25mm and 50mm amplitudes at 1Hz are carried out with both probes. The resulting time series data are compared to a theoretical fifth order Stokes solution. While overall agreement is good for both types of probe, optical wave gauge data are found to provide a better fit to the theoretical solution, especially in the vicinity of wave crests.

WS1.14 SMITH, H. C. M., SMITH, G. H., VENUGOPAL, V. & DAVEY, T.: “Analysis of potential power output of a device using a wave-by-wave approach”, *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/index.html>

The assessment of energy production from a wave energy converter commonly uses a stochastic approach. For short-term evaluations, a sea state can be represented in the frequency domain by an energy density spectrum. If a suitable frequency-dependent transfer function for the device is defined, an estimate of the total energy output for that specific sea state can be made. However, using a spectral averaging of the sea state in this way fails to account for short-term events that may significantly alter the output estimated using the spectral approach. This paper uses a ‘wave-by-wave’ method to assess the potential energy production of a hypothetical device, using recorded time series of sea surface elevation. The device is modelled as a damped linear oscillator, with the assumption that the device can be rapidly ‘retuned’ to maximise its response to changing wave properties. The method involves calculating the power output for each individual wave in the time series for a range of tuning rates and power transfer function (PTF) bandwidths. The average power output for each time series is then compared with estimates made using the traditional spectral method. The results illustrate the extent to which the estimates of power output differ depending on the rate of tuning and bandwidth of the PTF.

WS1.15 INGRAM, D. M., SMITH, G., VILLATE, J., JONSTONE, C. & BITTENCOURT FERREIRA, C.: “The development of technology evaluation protocols for the equitable evaluation of marine renewable energy converters”. *Coasts, Marine Structures and Breakwaters 2009: Adapting to change*. Edinburgh, Scotland, UK, 16-18 September 2009. <http://www.ice-breakwaters.com/>

WS1.16 INGRAM, D. M., GAO, F., CAUSON, D. M., MINGHAM, C. G. & TROCH, P.: “Numerical investigations of wave overtopping at coastal structures”, *Coastal Engineering*, vol. 56, issue 2, (2009), pp. 190–202. <http://www.sciencedirect.com/science/article/pii/S037838390800077X>

Under the numerical modelling work package of the EU funded CLASH project, the time accurate, free surface capturing, incompressible Navier–Stokes solver AMAZON-SC has been applied to study impulsive wave overtopping at Samphire Hoe, near Dover in the United Kingdom. The simulations show that the overtopping process on this vertical, sheet pile, seawall is dominated by impulsive, aerated, near vertical overtopping jets. In order to perform the simulations AMAZON-SC has been extended to incorporate an isotropic porosity model and for validation purposes the solver has been applied to study overtopping of a low crested sea dike and a 10:1 battered wall. The results obtained for the battered wall and Samphire Hoe tests are in good agreement both with predicted overtopping discharges calculated using the UK overtopping manual and with available experimental results.

WS1.17 SARUWATARI, A., WATANABE, Y. & INGRAM, D. M.: “Scarifying and fingering surfaces of plunging jets”. *Coastal Engineering*, Volume 56, Issues 11-12, November-December 2009, Pages 1109-1122, ISSN 0378-3839, DOI: 10.1016/j.coastaleng.2009.08.007. <http://www.sciencedirect.com/science/article/pii/S0378383909001227>

The local surface deformation resulting from the oblique impact of a columnar water jet has been computed, using a three-dimensional large eddy simulation, as a model of the overturning jet of a

breaking wave. The emergence of the secondary jet from the front face of the initial jet has been examined and the organisation of the vortices within the jet characterised. As the secondary jet emerges, the vorticity field becomes unstable under the action of the strong shear beneath the jet surface and pairs of longitudinal counter-rotating vortices stretched along the direction of the jet projection are formed. The presence of these longitudinal vortex pairs creates convergent surface flows, resulting in the formation of longitudinal scars on the rear face of the projecting jet. Following significant growth of the scars on both its upper and lower surfaces, the jet decouples into fingers. The lateral widths of the longitudinal vortices provide a minimum measure of the finger size. A horizontal Froude number  $Fr_h$ , representing a measure of strength of horizontal shear in a gravity-dominated impacting flow is defined, which characterises the organisation of the longitudinal vortices occurring in the shear flow, and the resultant formation of scars and fingers. For higher  $Fr_h$ , stronger longitudinal vortices and deeper scars are formed at longer lateral intervals, enhancing the fingering process during the splashing event. Fundamental features of material transport in the vicinity of the surface of jets (e.g. gas transfer across a sea surface) are related to the entrainment of surface fluid by the longitudinal vortices, and is thus also characterised by  $Fr_h$ .

WS1.18 PAYNE, G. S., TAYLOR, J. R. M. & INGRAM, D. M.: “Best practice guidelines for tank testing of wave energy converters”, *Journal of Ocean Technology*, vol. 4, issue 4, (2009), pp. 38–70.  
**Invited paper** [www.journalofoceantechnology.com](http://www.journalofoceantechnology.com)

Experimental tank testing is a key aspect of wave energy conversion research. The performance of designs can be assessed in an accessible and controlled environment and at a fraction of the cost of sea trials.

Wave energy converter (WEC) tank testing is complex and has its own specificities compared with model testing of ships and offshore structures. This largely reflects the fact that the main quantity of interest is wave energy: how much is available and how much is harvested by the model.

This paper provides an extensive overview of the various aspects of WEC tank testing. These are divided into three categories: physical model, measurements, and wave generation. For each of them, current best practice guidelines are given.

WS1.19 ORTEGA, J. & SMITH, G. H.: “Hilbert-Huang transform analysis of storm waves”, *Applied Ocean Research*, vol. 31, issue 3, (2009), pp. 212–219.  
<http://www.sciencedirect.com/science/article/pii/S0141118709000868>

We use the Hilbert–Huang transform (HHT) for the spectral analysis of a North Sea storm that took place in 1997. We look at the contribution of the different Intrinsic Mode Functions (IMF) obtained using the Empirical Mode Decomposition algorithm, and also compare the Hilbert Marginal Spectra and the classical Fourier Spectra for the data set and the corresponding IMFs. We find that the number of IMFs needed to decompose the data and the energy associated to them is different from previous studies for different sea conditions by other authors. A tentative reason for this may lie in the difference in the sampling rate used.

WS1.20 SELLAR, B. G., BRUCE, T. & BRYDEN, I.: “Real-time, wide area wave field measurement”, *Proc. of 20th International Offshore and Polar Engineering Conference – ISOPE 2010*, vol. 1, pp. 782-787, 20th – 25th June 2010, Beijing, China.  
<http://www.isopec.org/publications/proceedings/ISOPE/ISOPE%202010/data/papers/10TPC-679Sellar.pdf>

A novel ocean surface tracking sensor is being developed at the University of Edinburgh in collaboration with Measurand Inc. of Canada with the goal of measuring wide-area wave field dynamics in unprecedented resolution in both space and time. Previous results using a demonstration device show regular wave period and wave height agreement with laboratory based sensors to 1% and 5% respectively. Preliminary irregular 2D tests show spectral parameters,  $T_{m01}$  and  $H_{m0}$ , in agreement to 9% and 16% respectively. These results have led to the development of several types of sensor based on the floating ribbon concept. The suitability of optical fiber technology for 3D short crested wave measurement is investigated along with the implementation of ancillary motion sensing pods based on inertial measurement technology. This paper summarises the development of the various ribbons,



focusing on the aim of integrating them in to an array or lattice and the subsequent encountered and forecasted “deployability” issues, including array mooring and mechanical behaviour.

WS1.21 MAGUIRE, A. E. & INGRAM, D. M.: “Wavemaking in a CFD code”, *Proc. Coastlab 10*, 28th September – 1st October 2010, Barcelona, Spain. <http://www.coastlab10.com/>

For most of the twentieth century, marine hydrodynamics has been limited to the two realms of theory and physical experiments. These methods of fluid flow analysis are limited through scope, cost and size of facility. The advent of high speed computing has brought with it's a new dimension for analyzing fluid flows, that of numerical modelling. Computational Fluid Dynamics (CFD) has the potential to offer an invaluable design tool to marine engineers. One such tool that CFD offers, is the possibility for a numerical wave tank. Physical wave tank are used in coastal engineering, naval engineering, offshore engineering and marine renewable engineering, but these facilities can be expensive and are limited in size and scale of the testing facility. A numerical wave tank can overcome these problems. But before and confidence can be placed in numerical results from a CFD code, a verification process should be conducted to assess both the coding and the mathematical calculations and the results should also be validated against a physical model or a known analytical solution. In this paper a commercial CFD code (ANSYS CFX) is assessed and verified for its suitability as a numerical wave tank. Both a temporal and spatial convergence study is conducted and the appropriate metrics analyzed. A validation procedure is implemented, comparing the obtained numerical solution to a known analytical solution using linear wave theory.

WS1.22 OKORIE, P.O., OWEN, A, & HOSSAIN, M.: “Implications of Froude Scaling in the Numerical Testing of a Generic Support Structure.” *3rd International Conference on Ocean Energy*; 6-8 October; Bilbao, Spain; 2010. <http://www.icoe2010bilbao.com/ing/index.aspx>

Numerical modelling is complementary method to laboratory techniques commonly used in testing tidal current energy devices. Using a classical flow over a cylinder as a case study, it was demonstrated that numerical modelling of tidal current energy devices is insensitive to boundary layer behaviour of Froude scaled models within the subcritical flow regimes.

WS1.23 GOOD, A., HAMILL, G., WHITTAKER, T. & ROBINSON, D.: “PIV Analysis of the Near Wake of a Tidal Turbine”, *Proc. of 21st International Offshore and Polar Engineering Conference- ISOPE 2011*, vol. 1 pp. 770-776, Maui, USA, 19-24 June 2011. <http://www.isopec.org/publications/proceedings/ISOPE/ISOPE%202011/data/papers/11TPC-201Good.pdf>

Particle image velocimetry (PIV) has been applied to measure the velocity profile within the near wake of a laboratory scaled model of a horizontal axis tidal turbine. Measurements have been taken for a number of arrangements to investigate the relative impact on the velocity profile of ambient conditions, the support structure, and energy extraction by the rotor.

WS1.24 OKORIE, P.O., OWEN, A, & POLLARD, P.: “Study of Coherent Structures Suitable for Numerical Testing of Tidal Current Energy Devices”. *9<sup>th</sup> European Wave and Tidal Energy Conference*”; 5-9 September; Southampton, UK; 2011. <http://www.ewtec.org/>

Turbulence in open channel is random and contains vortices. An approach to generate significant vortex structures suitable for testing energy devices submerged in turbulent flow has been demonstrated using ADCP data integrated into LES of an open channel flow. The approach is based on the premise that turbulent velocity profiles from real site averaged within a small time resolution is influenced by waves, seabed roughness, shape of the coastline and other physical and natural processes evident in the experimental velocity profile.

Significant eddies were visualised from the numerical simulation results when results were compared with simulations done by specifying the classical  $1/7^{\text{th}}$  power law and uniform flow profiles as boundary conditions. This study further demonstrates the possibility of representing a large scale flow process in a small scale numerical domain.

WS1.25 PASCAL, R., PAYNE, G.S., & BRYDEN, I, G.: “Parametric models for WEC performances.” *Proceedings of the 9th European Wave and Tidal Energy Conference*. 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

Wave energy is an emerging and promising renewable energy technology. As the first pre-commercial and commercial prototypes are being tested at sea, there is a need for developers, governments and investors to be able to reliably estimate the energy production of devices as a function of the sea states they are to be deployed in. This estimate has traditionally relied on only two sea state parameters, the significant wave height and the energy period, which do not account for frequency or directional spreading. The present paper investigates the suitability of further parameters to refine performance predictions. This is achieved through extensive wave tank testing of three types of wave energy converters (WECs) with different directionality properties. Statistical analyses of the measurements show the significant impact of frequency and directional spreading on WECs performance. Parametric models of the devices performances were devised for numerous sea states parameters. Those results suggest that the traditional estimation method should be extended in order to include such parameters.

WS1.26 TOPPER, M. B. R. & INGRAM, D, I.: “Identifying the Frontier of Knowledge for Marine Renewable Energy Research” *Proceedings of the 9th European Wave and Tidal Energy Conference*. 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

Verification and validation techniques can provide a strategic framework for improving the predictive capability of numerical models used in the marine renewable energy sector. In addition, it is proposed that the adoption of open source community models make implementing such strategies more straightforward. A technique of particular interest is the Phenomena Identification and Ranking Table (PIRT). Such a table can be used to quantify the current state of knowledge and the subsequent requirements for improving the predictive capability of modelling software. After assessing and collating the current software usage trends within the wave and tidal numerical modelling community, an example PIRT is presented for tidal energy converter hydrodynamics.

WS1.27 TOPPER, M. B. R., FOREHAND, D. I. M., & INGRAM, D, I.: “Using a Galerkin Method to Calculate the Velocity of Vortex Wake Sheets” *Symposium of The International Association for Boundary Element Methods (IABEM)*, Brescia, 2011 [www.iabem2011.it/](http://www.iabem2011.it/)

Boundary element methods are commonly used in the fields of aeronautics and hydrodynamics to calculate flows about bluff and lifting bodies. When lifting bodies are considered, a vortex sheet, emanating from the lifting body’s trailing edge, must be included in the model in order to correctly account for the lift. Low order discretisations, particularly for unsteady simulations, do not calculate sufficiently accurate velocities on these sheets, which then leads to instabilities and erroneous solutions. As such, many efforts have been made to develop boundary element lifting solutions using higher order discretisations. For the vortex wake sheet, only the difference in potential between the top and bottom of the sheet is known and thus differentiating this quantity does not provide the required average of the velocity between the top and bottom of the sheet. The only available method to calculate the velocity of a vortex sheet is to directly differentiate the boundary integral equation producing a hypersingular boundary integral equation. Recent work has shown that a Galerkin limiting technique can be used to calculate the solution to the hyper-singular boundary integral equation at the edges and corners of high order piecewise elements in three dimensions. This paper considers the application of the aforementioned Galerkin method to solving for the velocity on vortex wake sheets in boundary element methods. Results will be presented along with a discussion of various improvements that can be made in order to enhance the stability of the method.

WS1.28 EMARAT, N., FOREHAND, D.I.M., CHRISTENSEN, E. D. & GREATED, C. A.: “Experimental and numerical investigation of the internal kinematics of a surf-zone plunging breaker”, *European Journal of Mechanics B/Fluids*. DOI: 10.1016/j.euromechflu.2011.09.002. 2011 [http://www.elsevier.com/wps/find/journaldescription.cws\\_home/600738/description](http://www.elsevier.com/wps/find/journaldescription.cws_home/600738/description)

Over the last couple of decades both the qualitative and quantitative understanding of breaking waves in the surf zone have greatly increased. This is due to the advances in experimental and numerical

techniques. However, few comparisons between these two different investigative techniques for surf-zone breaking waves have been reported.

In this study, a comparison is made between the experimental and numerical investigation of the internal kinematics of a surf-zone plunging breaker. The full-field velocity measuring technique known as Particle Image Velocimetry (PIV) is used in the experiments. In the hybrid numerical scheme, the main model solves the Navier-Stokes equations using a Finite Volume method and the free-surface is simulated using a Volume of Fluid (VOF) method. An important feature of this work is that, unlike in most other comparisons between numerical and experimental results, the exact geometry of the physical wave flume and the exact motion of the physical wavemaker are duplicated in the numerical wave tank. To achieve this, an additional numerical model using a Boundary-IntegralMethod (BIM) is employed to generate the input conditions for the Navier-Stokes solver.

Very good agreement was found for all comparisons: free-surface elevations, velocity vectormaps, velocity profiles and velocity-magnitude contours. However, some small discrepancies were observed. In the free-surface elevation comparisons a slight time lag was observed in the numerical results and it is suggested that this was due to the small amount of smoothing applied in the BIM to enable it to continue to supply input data to the Navier-Stokes solver well beyond the breaking of the wave. In addition, some small differences were also found between the numerically predicted velocity distributions and those measured in the experiments. These disagreements occurred mostly in the aerated region and it is proposed that they could be caused by errors in the PIV velocity data due to air bubble effects. However, they could also be attributed to the fact that no turbulence model is used in the numerical scheme and it is these aerated areas where the turbulence levels are the highest.

WS1.29 MAGUIRE, A. E. & INGRAM, D. M.: “On geometric design considerations and control methodologies for absorbing wavemakers”, *Coastal Engineering, Volume 58, Issue 2, February 2011, Pages 135-142, ISSN 0378-3839, DOI:10.1016/j.coastaleng.2010.09.002.*  
<http://www.sciencedirect.com/science/article/pii/S0378383910001341>

This paper investigates the effects that geometry and control have on the absorption characteristics of wavemakers. It presents the hydrodynamic coefficients for piston and bottom hinged flap wavemakers and also for two novel wavemaker profiles. Absorption efficiencies are presented for wavemakers using one, two and three control coefficients for reactive control. This is then used to analyse the absorption efficiency of each of the different wavemakers based upon the geometry and the control strategy used. It is shown that the amount of absorption for a given paddle differs greatly depending on the choice of control coefficients used to implement complex conjugate control. Increased absorption can be achieved over a broader bandwidth of frequencies when the geometry of the wavemaker is optimised for one specific frequency.

WS1.30 INGRAM, D. M., SMITH, G. H., FERRIERA, C. B. & SMITH, H.: “Protocols for the Equitable Assessment of Marine Energy Converters.” 2011 <http://www.equimar.org/>

EquiMar involved about 60 scientists, developers, engineers and conservationists from 11 European countries working together to find ways to measure and compare the dozens of tidal and wave energy devices, proposed locations and management systems currently competing for funds, so governments can invest in the best ones and get marine energy on tap fast. The team has delivered a suite of “high level” protocols – general principles to allow fair comparison of marine energy converters testing and evaluation procedures. EquiMar protocols cover site selection, device engineering design, scaling up designs, deployment of arrays, environmental impact on flora, fauna & landforms, and economic issues. The final EquiMar protocols establish a sound base for future marine energy standards currently being developed by IEC Technical Committee 114. This project received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement number FP7-021338.

<b>WORKSTREAM 2 - Optimisation of collector form and response</b>
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- WS2.1 MCCABE, A. P. & AGGIDIS, G.A.: “Optimum mean power output of a point absorber wave energy converter in irregular waves”, *Conf. Sustainable Energy UK: Meeting the science and engineering challenge*, 13-14th May 2008, St Anne's College, Oxford.  
<http://pia.sagepub.com/content/223/7/773#aff-1>

This article presents an assessment of the optimum mean power output of a point-absorber wave energy converter (PAWEC) in irregular wave climates. A first-order method is used to calculate the mean power spectrum of the device in waves of dissimilar spectra. JONSWAP spectra with different peak enhancement parameters are used to show the effect of energy concentration within the wave spectrum on the device mean power spectrum. A comparison of the optimum mean power output of a PAWEC in an irregular wave climate with that in an energy-equivalent regular wave climate is made to show the influence of the combination of wave spectrum and power output characteristics on the former. The principle is demonstrated by results obtained with the simulation of a PAWEC collector. An evaluation is made of the difference between the optimum mean power output of the device and the mean power output achieved using a simple, standard control method. The resulting difference in energy output with measured data from a possible site is also assessed. The implications of the results on the appraisal of device performance are considered.

- WS2.2 MCCABE, A. P., AGGIDIS, G.A. & WIDDEN, M.: “Some aspects of tuning wave energy converters in irregular waves”, *Proc. World Renewable Energy Congress X*, 19-25 Jul 2008, Glasgow, ISBN: 978-008-056-8973. <http://www.wrenuk.co.uk/>

This paper presents the results of a study into the ‘tuning’ of a device in irregular seas. The results are obtained using computer models of two device configurations, employing a simple ‘sea-state-tuning’ control strategy, one in which the system is tuned to a single frequency for the duration of each sea state. A first-order method is used to calculate the mean power output of the device in each case. Two demonstration simulation examples of wave energy collectors are used, one cylindrical and the other a cuboid. The cylindrical collector is modelled as a single-degree-of-freedom system moving only in the heave mode, and, together with the cuboid collector, as a coupled two-degrees-of-freedom system, moving in the pitch and surge modes. An iterative method is used to find the appropriate tuning characteristics for maximum mean power output in a selection of sea states of constant significant wave height.

Results show that, in the single-degree-of-freedom heave case, the reciprocal of the energy period of the sea state provides a suitable tuning frequency for the control of the device. However, this is not the case in the two-degrees-of-freedom pitch and surge case. In this case, as the energy period increases, the appropriate tuning period for maximum mean power output diverges from the energy period. The amount of divergence from the energy period is found to increase as the energy is distributed more widely across the wave spectrum. The amount of divergence from the energy period also increases as more external damping is applied to the system. The difference in behaviour results from the difference in the power characteristics of the heave and surge modes, that of the unconstrained heave mode constantly increasing as the period increases, whereas that of the surge mode decreases to zero as the period increases. The results indicate that, even to a first approximation, the tuning of a device operating in coupled pitch and surge modes for maximum mean power output in irregular waves presents a significant challenge.

- WS2.3 MCCABE, A. P. & AGGIDIS, G.A.: “A preliminary study into optimising the shape of a wave energy collector using a genetic algorithm”, *The 1st International Conference on Sustainable Power Generation and Supply (SuperGen)*, Nanjing, China, 6-7 April 2009.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5348027](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5348027)

This paper describes an initial study into the optimisation of the shape of a wave energy collector using a genetic algorithm. The study investigates three descriptions of the surface geometry of a surging device, which are both compatible with panel-based hydrodynamic analysis software and form a suitable representation in the genetic algorithm. The analysis has been simplified by considering only the two-dimensional problem, that of optimising the cross-sectional shape of the surging body. Real-valued

representation and continuous search space recombination and mutation are used in the genetic algorithm. A basic power absorption cost function is used to assess the relative performance of each candidate shape. The contribution of the results to the overall understanding of the optimization procedure and the direction of future research is discussed. In addition, the relative merits of the different geometric descriptions, and their value for further development are considered.

WS2.4 BHINDER, M. A., RAHMATI, M. T., AGGIDIS, G. A., CHAPLIN, R. V., MINGHAM, C. G. & CAUSON, D. M.: “A joint numerical and experimental study of a surging point absorbing wave energy converter”, *28th ASME International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2009)*, Honolulu, Hawaii, 31 May - 5 June 2009.  
[http://www.flow3d.com/pdfs/tp/mar\\_tp/FloSci-Bib22-09.pdf](http://www.flow3d.com/pdfs/tp/mar_tp/FloSci-Bib22-09.pdf)

This paper presents the findings from using several commercial computational fluid dynamics codes in a joint numerical and experimental project to simulate WRASPA, a new wave energy converter (WEC) device.

A series of fully 3D non-linear simulations of WRASPA are presented. Three commercial codes STAR-CCM, CFX and FLOW-3D are considered for simulating the WRASPA device and final results are presented based on the use of Flow-3D. Results are validated by comparison to experimental data obtained from small scale tank tests undertaken at Lancaster University (LU).

The primary aim of the project is to use numerical simulation to optimize the collector geometry for power production over a range of likely wave climates. A secondary aim is to evaluate the ability of commercial codes to simulate rigid body motion in linear and non-linear wave climates in order to choose the optimal code with respect to compute speed and ease of problem setup. Issues relating to the ability of a code in terms of numerical dissipation of waves, wave absorption, wave breaking, grid generation and moving bodies will all be discussed.

The findings of this paper serve as a basis for an informed choice of commercial package for such simulations. However the capability of these commercial codes is increasing with every new release.

WS2.5 BHINDER, M. A., RAHMATI, M. T., AGGIDIS, G. A., CHAPLIN, R. V., MINGHAM, C. G. & CAUSON, D. M.: “Numerical and experimental study of a point absorbing wave energy converter in regular and irregular waves”, *International Conference on Clean Electrical Power: Renewable Energy Resources Impact*, Capri, Italy, 9-11 June, 2009.  
<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5211995&isnumber=5211951>

This paper describes recent numerical modelling of a new wave energy converter WRASPA (wave-driven, resonant, arcuate action, surging power-absorber). The presented results are based on a range of. Also the experimental setup is outlined to illustrate the brief design principles of the device. A comparison of experimental and numerical results is performed as part of the validation process. The interaction of waves with WRASPA device has been simulated using a commercial code flow-3D as one of the primary objectives of this project. The ability of the method to compute a range of linear waves and coupled motion of the device is discussed. The code's ability to deal with wave propagation and interaction with rigid moving structures is evaluated.

WS2.6 AGGIDIS, G. A.: “The Lancaster marine energy research in the context of the International Ocean Energy Symposium 2009 in China”, **Invited Paper**, *International Ocean Energy Symposium 2009 (IOES-2009)*, Harbin, China, 17-18 September 2009.  
<http://derc.hrbeu.edu.cn/%E6%96%B0%E8%8B%B1%E6%96%87%E4%BC%9A%E8%AE%AE%E9%80%9A%E7%9F%A5.htm>

At Lancaster University, research on Marine Energy and Wave Energy Converters (WECs) began in 1974 and is continuing today. A number of devices were conceived and studied, while generic research was carried out into the theory of WECs and their systematic design. Lancaster University Renewable Energy Group has a track record of internationally recognised research with the associated abilities to collaborating widely, both externally and internally having experience and expertise in formulating and

use of hydrodynamic modelling as a way of predicting the performance of wave energy converters, control, and the fundamental science of wave energy capture by point-absorber converters, supported by both numerical modelling and experimental work in the state of the art wave tank.

Tidal stream energy and wave energy taken together could in principle meet approximately 15-20% of UK electricity demand. Research at Lancaster is concentrating on a niche area of high-lift vertical axis tidal stream devices for tidal stream energy generation able to operate and capture power efficiently on shallow estuarine environments. The group is also involved with tidal stream technologies for the North West tidal energy projects and the EPSRC SuperGen Marine generic research. The UK's outstanding tidal resources could provide at least 10% of the country's electricity through a combination of technologies. A Severn barrage alone could potentially supply up to 5%, while the North West coast line region could provide up to another 5%. Since the summer of 2006 the group has been actively involved with the North West tidal projects from the Mesrey to the South up to the Solway in the North developing and occupying the founding chair of the North West Tidal Energy Group. Currently the group is involved with the collaborative feasibility study into producing tidal energy in the Solway Firth between England and Scotland.

WS2.7 STABLES, M. A., AGGIDIS, G., TAYLOR, C. J., CROSS, P. & GUNN, K: "Linear Control of a Nonlinear Power Take-Off Simulation for Wave Energy Conversion in Irregular Seas", *International Ocean Energy Symposium 2009 (IOES-2009)*, Harbin, China, 17-18 September 2009. <http://cpfd.cnki.com.cn/Article/CPFDTOTAL-ZJHY200909001013.htm>

This article discusses a control strategy for optimal energy capture in irregular seas by focusing on control of the power take off (PTO) element of a point absorber wave energy converter. The research is based on a nonlinear simulation of a PTO hydraulic circuit, in which the piston velocity and generator torque act as 'disturbance' and control actuator variables respectively, whilst the damping force is the output variable under control. The piston velocity is generated by a hydrodynamic simulation model of a heaving buoy, acting with one degree of freedom, that reacts to both the damping force from the PTO simulation and the irregular sea wave profile. The damping force set point will be obtained from an associated power capture optimisation module and may be time varying. However, it is clear that such an adaptive tuning system also requires high performance 'low-level' control of the device actuators, in order to fully realise the benefits of optimisation. In this regard, the present article illustrates use of the Proportional-Integral-Plus (PIP) control methodology applied to the PTO simulation. In their simplest linear form, such PIP controllers do not account for the interconnected system variables mentioned above. For this reason, the research also considers 'feed-forward' and 'state-dependent' forms of PIP control, in which the piston velocity is appended to a non-minimal state space representation of the system.

WS2.8 BHINDER, M. A., RAHMATI, M. T., AGGIDIS, G. A., CHAPLIN, R. V., MINGHAM, C. G. & CAUSON, D. M.: "Numerical and experimental flow analysis of a wave energy converter", *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/>

This study presents numerical modelling of a WEC (wave energy converter) along with some details of the experimental setup. Issues related to the numerical modelling of the single DOF (degree-of-freedom) motion of a surging point absorber WEC are outlined and a comparison with experimental data is presented. A commercial CFD code Flow-3D is used for numerical modelling and the ability of the code to simulate free surface linear waves and wave structure interaction is evaluated.

The work is aimed at simulating a surging wave energy converter to achieve an optimized shape and to predict output power at a higher or full scale. The findings of this study may also serve as a reference point for the use of a commercial code such as Flow-3D for the simulation of such problems.

WS2.9 MCCABE, A. P., AGGIDIS, G. A. & WIDDEN, M. B.: "A pilot study into the optimization of the shape of a wave energy collector by genetic algorithm", *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/>

This pilot study forms part of the optimization of the shape of a wave energy collector to improve energy extraction using generic algorithms. Two main types of generic algorithms exist, differentiated by the use of binary or real numbers as object descriptors. The study is intended to ascertain if one type is more suited to the specific problem by comparing the performance of two algorithms. The algorithms optimize the shape of a bisymmetric wave energy collector moving in two degrees of freedom (surge and pitch). The collector is described by ruled surfaces in one quadrant, defined by the positions of seven vortices. The cost function is based upon a first-order model of the system, with the collector optimally tuned to a number of incident regular waves with a generalised occurrence distribution. High velocities and large collector volumes are penalized. An assessment of the performance of the two algorithms is made, looking at the improvement in value and change in diversity of the respective populations. A comparison is also made of the computational requirements of the different parts of the optimization process.

WS2.10 WINCHESTER, J. D. & QUAYLE, S.: “Torque ripple and variable blade force: A comparison of Darrieus and Gorlov-style turbines for tidal stream energy conversion”, *8<sup>th</sup> European Wave and Tidal Energy Conference*, Uppsala, Sweden, September 2009. <http://www.ewtec2009.se/>

There are two main types of lift driven vertical axis turbine which can be used for capturing energy from tidal streams. These are the straight bladed “Darrieustype” and the helically shaped “Gorlov-type”. The Darrieus-type turbine can suffer from vibrations in the shaft due to torque variations, known as “torque ripple”. Gorlov-type turbines ought to reduce this problem but suffer from variations in force distribution along the length of turbine blade. The double multiple streamtube model (a blade element momentum model), with the Gormont-Berg adaptation for dynamic stall, is used to analyse the blade forces and shaft torques. The results show the extent to which torque ripple or variable blade force is effected by various other design choices, such as blade thickness, blade camber or turbine solidity. From these some of the requisite turbine characteristics are derived.

WS2.11 MCCABE, A. P. & AGGIDIS, G. A.: “The optimization of the form of a wave energy collector using genetic algorithms”, *Invited for publication by Ocean Press*, Beijing, China, September 2009. [http://isbndb.com/d/publisher/china\\_ocean\\_press.html](http://isbndb.com/d/publisher/china_ocean_press.html)

This paper describes the initial studies carried out in a research programme looking into the optimization of the shape of a wave energy collector using a genetic algorithm. The aim is a systematic approach to the optimisation of collector form for a series of generic device classes. The form of the active surface will be allowed to evolve using genetic algorithms in order to find the optimal design parameters. Optimal collector forms will improve energy capture rates and inform the design of the next generation of wave energy converters. The research seeks to determine the existence, or otherwise, of optimal designs for the physical form of a wave energy collector, in terms of its response. To do so requires the definition of the constraints and parameters needed to formulate a suitable cost function for systematic optimization. In addition, can such designs be found using genetic algorithms, with a combination of numerical modelling and laboratory experimentation?

WS2.12 MCCABE, A. P. & AGGIDIS, G. A.: “Optimum Mean Power Output of a Point Absorber Wave Energy Converter in Irregular Waves”, *Proceedings of IMechE Part A: Journal of Power and Energy*, vol. 223, issue A7, (2009), pp. 773–781. <http://pia.sagepub.com/>

This article presents an assessment of the optimum mean power output of a point-absorber wave energy converter (PAWEC) in irregular wave climates. A first-order method is used to calculate the mean power spectrum of the device in waves of dissimilar spectra. JONSWAP spectra with different peak enhancement parameters are used to show the effect of energy concentration within the wave spectrum on the device mean power spectrum. A comparison of the optimum mean power output of a PAWEC in an irregular wave climate with that in an energy-equivalent regular wave climate is made to show the influence of the combination of wave spectrum and power output characteristics on the former. The principle is demonstrated by results obtained with the simulation of a PAWEC collector. An evaluation is made of the difference between the optimum mean power output of the device and the mean power output achieved using a simple, standard control method. The resulting difference in energy output with measured data from a possible site is also assessed. The implications of the results on the appraisal of device performance are considered.

- WS2.13 MCCABE, A. P., AGGIDIS, G. A. & WIDDEN, M. B.: “Optimizing the shape of a surge-and-pitch wave energy collector using a genetic algorithm”, *Renewable Energy, Volume 35, Issue 12, December 2010, Pages 2767-2775, ISSN 0960-1481*, DOI: 10.1016/j.renene.2010.04.029. <http://www.sciencedirect.com/science/article/pii/S0960148110001965>

This study forms part of research into the optimization of the shape of a wave energy collector to improve energy extraction using genetic algorithms. The wave energy collector geometry uses a parametric description based upon bi-cubic B-spline surfaces, generated from a relatively small number of control points to reduce the dimensionality of the search space. The collector shapes that are optimized have either one or two planes of symmetry. An elementary cost function is used to determine the performance of each candidate solution. The collectors move in two degrees of freedom (surge-and-pitch), and are optimally tuned to absorb the greatest power from a number of incident regular waves, the results being weighted according to a generalized occurrence distribution. High velocities and large collector volumes are penalized. A benchmark collector shape, against which the optimized shapes are compared, is identified. The overall optimization strategy entails performing repeated runs of the algorithm for a fixed number of generations, then restarting the optimization with the run that produces the best result. An appraisal of the results is made, looking at the performance of all the shapes assessed as well as those deemed the best.

- WS2.14 MCCABE, A. P., AGGIDIS, G. A. & WIDDEN, M. B.: “The effect of wave climate on the optimization of the shape of a wave energy collector by genetic algorithm”, *9th European Wave and Tidal Energy Conference*, 5-9 September; Southampton, UK, September 2011. <http://www.ewtec.org/>

Wave energy extraction requires the conversion of the energy within the waves to drive the power take off system, often by means of a principal interface, or collector. This paper describes part of the development of a robust systematic method of optimizing the collector shape to improve energy extraction. In this study, the collector geometry uses a parametric description based upon bi-cubic B-spline surfaces, generated from a relatively small number of control points to reduce the dimensionality of the search space. The collector shapes that are optimized have one plane of symmetry and move in one degree of freedom (surge). The cost function used to determine the performance of each candidate solution estimates the annual energy production in two wave climates, based upon data from sites in the north-east Atlantic Ocean and the central North Sea. A control algorithm is used to keep the collector displacement and power delivery within stipulated limits. The overall optimization strategy entails performing repeated runs of the algorithm for a fixed number of generations, then selecting the best overall result. The shapes obtained for each wave climate are compared in terms of size and performance and marked differences are observed in each case.

- WS2.15 WINCHESTER, J. D. L., MCCABE, A. P. & AGGIDIS, G. A.: “CFD Analysis of a Multi-Axis Wave Energy Converter with Novel Geometry”, *9th European Wave and Tidal Energy Conference*, 5-9 September; Southampton, UK, September 2011. <http://www.ewtec.org/>

This study forms part of research into the optimisation of wave energy collector shape to improve energy extraction. A novel shape was devised using a genetic algorithm and a potential flow solver. Three dimensional Reynolds-Averaged Navier-Stokes (RANS) was then used to analyse the performance of the shape when allowed multi-axis mobility in a regular sea. After verification, the RANS solver enabled the capabilities and limitations of potential flow theory to be explored and provided scope for a more sophisticated optimisation procedure to be undertaken.

- WS2.16 HILLMANN, M., LI, M. & QUAYLE S.: “Numerical Investigation of a Novel Breakwater Combining Coastal Defence and Energy Generation in the Near Shore Environment”, *9th European Wave and Tidal Energy Conference*, 5-9 September; Southampton, UK, September 2011. <http://www.ewtec.org/>

A new numerical model was developed to study surface waves interacting with a novel design of breakwater in combinations of energy generation and coastal defence. Preliminary model results suggest



complex flow structures around the breakwater considerably influences energy generation. Further detailed analysis of model results and comparisons with laboratory tests need to be carried out to optimise design of the structure.

WS2.17 GUNN, K., TAYLOR, C. J. & LINGWOOD, C.: “An Independent Validation of the Optimality of Latching and De-clutching Control by Evolutionary”, *9th European Wave and Tidal Energy Conference*, 5-9 September; Southampton, UK, September 2011. <http://www.ewtec.org/>

Latching and de-clutching have been proposed for controlling Wave Energy Converters (WEC), for waves of period higher and lower than the natural period of the WEC, respectively. Historically, the selection of these control strategies was based on the a priori assumption of the need to match the phase of motion of the WEC collector to the incident wave force, and to minimise the applied forces. In this paper, a standard time-domain model of a WEC is controlled by time-varying damping (representing power extracted by a generator). By the application of a novel evolutionary algorithm and artificial neural networks, the time varying damping is optimised to maximise the mean power extraction in a variety of sea states, including both monochromatic and polychromatic (Bretschneider) seas. This method can be used to optimise any control strategy. The resulting time-varying damping coefficients suggest that the resultant generic control strategy in fact represents the specific cases of latching and de-clutching. Furthermore, it is suggested that both of these strategies are required in combination in all sea states for optimum power extraction. These results are achieved with no a priori assumptions regarding the nature of optimum control (with regard to forces applied of phase of motion) and thus represent an independent, implicit validation of the latching and de-clutching control strategies.

#### ***Accepted and/or In Press***

WS2.18 WHITTAKER, T. & FOLLEY, M.: “Nearshore Oscillating Wave Surge Converters and the Development of Oyster.” *Philosophical Transactions of the Royal Society A*, *In press* <http://rsta.royalsocietypublishing.org/>

Oscillating Wave Surge Converters (OWSCs) are a class of wave power technology that exploits the enhanced horizontal fluid particle movement of waves in the nearshore coastal zone with water depths of 10 to 20 metres. OWSCs predominantly oscillate horizontally in surge as opposed to the majority of wave devices, which oscillate vertically in heave and usually deployed in deeper water. The characteristics of the nearshore wave resource are described along with the hydrodynamics of OWSCs. The variables in the OWSC design space are discussed along with a presentation of some of their effects on capture width, frequency bandwidth response and power take off characteristics. There are notable differences between the OWSCs under development and these are highlighted.

The final section of the paper describes Aquamarine Power’s 315kW Oyster 1 prototype, which was deployed at the European Marine Energy Centre in August 2009. Its place in the OWSC design space is described along with the practical experience gained. This has led to the design of Oyster 2 which is currently under development.

It is concluded that nearshore OWSCs are serious contenders in the mix of wave power technologies. The nearshore has a narrower directional spread than offshore, the largest waves are filtered out and the exploitable resource is typically only 10% to 20% less in 10m depth compared to 50m depth. Regarding the devices, a key conclusion is that OWSCs such as Oyster primarily respond in the working frequency range to the horizontal fluid acceleration; Oyster is not a drag device responding to horizontal fluid velocity. The hydrodynamics of Oyster is dominated by inertia with added inertia being a very significant contributor. It is unlikely that individual flap modules will exceed 1MW in installed capacity due to wave resource, hydrodynamic and economic constraints. Generating stations will be made up of line arrays of flaps with communal secondary power conversion every 5 to 10 units.

<b>WORKSTREAM 3 - Combined wave and tidal effects</b>
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WS3.1 BRYDEN, I.G., COUCH S.J., OWEN, A. & MELVILLE, G.: “Tidal Current Resource Assessment”, *Proc IMechE Part A: J.Power and Energy, Volume 221, Number 2 / 2006, pp125-154, ISSN 0957-6509*

<http://www.see.ed.ac.uk/~ibryden1/REE/2007%20material/Tidal%20Power%2814-2-207%29/methodology%20for%20tidal%20current%20resource%20assessment.pdf>

This paper outlines present thinking on the determination of accessible tidal current resources within channels and other potentially exploitable locations. The fundamental principles behind tides and tidal currents are briefly discussed and the implications of temporal and spatial variations on the evaluation of the resources considered in the context of artificial energy exploitation. The thinking behind the flux approach to resource estimation is presented and an example based on the Pentland Firth is considered. The impact of energy extraction on the flow patterns is considered in both one and two dimensions and the principles required for three-dimensional analyses are presented in a generic form.

WS3.2 BRYDEN, I.G.: "The Marine Energy Resource Constraints and Opportunities", *Proc ICivE Maritime Engineering, 159 issue MA2, (2006), pp 55 to 65, ISSN: 1741-7597*

<http://www.icevirtuallibrary.com/content/article/10.1680/maen.2006.159.2.55>

The British Isles are blessed with highly energetic coastal waters, which offer opportunities for the exploitation of waves and tides for the generation of electricity. This paper looks at prospects for, and constraints upon, the long-term economic development of the wave and tidal resources. Technology already exists which is capable of the effective harnessing of marine resources. Proponents have estimated that up to 40% of the UK electricity supply could, eventually, come from wave and tidal sources. More conservative estimates suggest that the potential is somewhat lower than this but still substantial. The wave resource is recognised as being the larger but the tides do offer some very real advantages. Specifically, they are predictable, as they are driven by regular astronomic mechanisms. In addition, the energy flux density in many of the most attractive sites is formidable, offering the prospect of large-scale generation with relatively compact technology. Developers of both wave and tidal technology share economic as well as technical challenges and these must be overcome if new industries are to be established. The solutions require effort by scientists, engineers and, crucially, politicians.

WS3.3 SUN, X., & BRYDEN, I.G. : “SuperGen Marine: Accelerator for UK Marine Renewable Energy Research (in Chinese)”, *New Energy Sources , August 2008, 4, August 2008, ISSN1671-5292/CN21-1*

[http://en.cnki.com.cn/Article\\_en/CJFDTOTAL-NCNY200804031.htm](http://en.cnki.com.cn/Article_en/CJFDTOTAL-NCNY200804031.htm)

There are rich marine resources in the UK, because of its unique geographic characteristics. The UK government is taking the lead in the development and utilization of tidal and wave energy in order to reduce its dependence on traditional fossil fuels, to create a diversified energy matrix and to cut carbon dioxide emissions. "SuperGen Marine" is an ongoing research programme supported by the UK government and it aims to increase scientific understanding of marine renewable resources and reduce the risk in marine energy development. This programme brings together leading academic and industry experts and covers all the key areas of energy conversions, delivery and storage. Many fruitful outcomes have been achieved. Undoubtly, its research models and methods would be the valuable references for the marine renewable energy studies being carried out in our country.

WS3.4 SUN, X., BRYDEN, I.G., JEFFREY, H., & FOREHAND, D. : “An Experimental Survey in the Wake of a Simulated Tidal Current Turbine”, *Journal of Marine Engineering and Technology, ProcIMarEST, No A12, September 2008, 13 to 22, ISSN 147-1548*

<http://www.imarest.org/Publications/TechnicalProceedings/JMET.aspx>

This paper presents two experimental test programmes, conducted in a water flow channel and a tow tank respectively, and devised to investigate the wake behind a simulated horizontal axis tidal current turbine. Both sets of experimental results have identified the wake as having a Gaussian-like shape and the wake

deficit recovering gradually with distance downstream. Also, although it is not directly representative of real operating conditions, the appropriateness of a towing tank for the model tidal current turbine testing has been supported, by having obtained compatible force and wake profiles in the two test programmes

WS3.5 IYER, A., HARRISON, G., WALLACE, A. R. & COUCH, S. J.: “Analysis and comparison of tidal datasets for resource assessment and network modelling”, *44th International Universities' Power Engineering Conference (UPEC 2009)*, Glasgow, Scotland, UK, 1-4 September 2009. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5429399>

The tidal resource is highly spatially and temporally variable. For tidal current energy to be economically exploited, certain conditions need to be fulfilled. Foremost, the strength of the resource needs to be quantified. This paper will build on and expand simplified analysis methods so far adopted for regional and national scale resource assessments. High quality data collection for interesting sites is highly desirable but very expensive. Existing publicly available datasets have therefore typically been used to examine the resource. A methodology is needed to combine all of the available datasets to produce an improved resource assessment methodology.

WS3.6 IYER, A., COUCH, S. J., HARRISON, G. & WALLACE, A. R.: “Analysis and comparison of tidal datasets”, *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/>

Tidal resources are highly variable, spatially and temporally. For tidal current energy to be economically exploited, certain conditions need to be fulfilled. Principally the strength of the resource needs to be quantified before it can be effectively utilised. This paper will build on and expand the simplified tidal analysis methods adopted in 1 and other simplified regional and national scale resource assessments. High quality data collection for interesting sites is highly desirable but expensive, difficult to extrapolate over a larger area, and hence unsuitable for national scale resource analysis. Existing publicly available datasets have so far typically been used to examine the resource. A methodology to combine all of the available datasets to produce an improved resource assessment methodology is desirable. Combining datasets will only be suitable if there is good correlation and consistency between them. The suitability of combining three UK wide datasets will be examined in this analysis. The data sources considered are: UK Moored Current Meter Data, UK Hydrographic Office publications, and the DTI Atlas of UK Marine Renewable Energy Resource. The datasets do not generally coincide spatially or temporally. Analysis to enable direct comparison of these datasets for a case study region will be presented. This will inform whether the methodology of analysis and combining of datasets has potential for application at larger scales. If with additional processing, datasets can be combined, considerable improvement will potentially be realised in analysing the UK tidal energy resource. Future work is intended to combine outputs from this research with similar datasets for other intermittent renewable resources in order to examine their combined output and their potential integration into the existing electrical network infrastructure.

WS3.7 EL-GEZIRY, T.M. & BRYDEN, I.G.: “The Circulation Pattern in the Mediterranean Sea: issues for modeller consideration”, *Journal of Operational Oceanography*, Volume 3, Number 2, August 2010, pp. 39-46(8), *IMarEst*, ISSN1755-8778 <http://www.imarest.org/Home.aspx>

The Mediterranean Sea is one of the most thoroughly studied water bodies in the world. Its location and geopolitical importance since before the rise of the Roman Empire has stimulated study since the early eras of human civilisation. More recently, the Sea, like many of the world's oceans, has attracted the attention of engineers considering the extraction of renewable energy. This paper outlines the complexity of the domains which underpinning modelling must consider.

The Mediterranean Sea is a semi-closed water body connected to the Atlantic Ocean through the Strait of Gibraltar in its far western extremity. The main basin is divided into two principal sub-basins, which together cover a surface area of  $2.5 \times 10^6$  km<sup>2</sup>, with a maximum measured depth of 5.1km. The Sea is characterised by its three distinct water masses: surface, intermediate and deep. These cover the whole Mediterranean basin and circulate independently. The general circulation pattern of the Sea has its own features and characteristics, which are described in this paper, drawing upon published research results.

WS3.8 BRYDEN, I.G.: “The Severn Barrage and Wave and Tidal Current Energy in the UK”, *Energy Focus Vol 26 No 3 December 2009, ISSN: 0265 – 1734* <http://www.pges.org.uk/>

WS3.9 EL-GEZIRY, T. M., BRYDEN, I. G. & COUCH, S. J.: “Environmental impact assessment for tidal energy schemes: an exemplar case study of the Strait of Messina”, *Journal of Marine Engineering and Technology (Proceedings of IMarEST Part A), issue 13, (2009), pp. 39–48.* <http://www.imarest.org/>

Tidal currents and ranges in the Mediterranean basin are generally low from a tidal energy perspective. The narrows through the Strait of Messina are an exception, exhibiting intensive tidal currents that have the potential for the economic exploitation. Maximum current velocities at spring peak tides through the Strait vary between 1.8m/s to more than 3m/s. Selection of suitable locations for tidal energy extraction for the exploitation of these natural tidal phenomenon is not, however, a simple process. Constraints must be satisfied, subject to basic criteria dependent upon local factors, technology limitation and economic consideration. In addition, the impact of large scale extraction on the underlying hydrodynamics, environment and ecology within the Strait has to be assessed and evaluated. This paper is a desk-based case study to show how a tidal resource may be environmentally assessed for energy extraction, using the Strait of Messina as an exemplar case

WS3.10 RADTKE, J., DENT, C. J. & COUCH, S. J.: “Capacity Value of Large Tidal Barrages”, *The 11<sup>th</sup> International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2010, June 2010, Singapore, pp. 331–336.* <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5528894>

This paper presents the first detailed capacity value calculation for tidal barrage generation, based on modelling of operational modes for the proposed 8-GW Severn Barrage scheme in Great Britain. The key finding is that the effective load carrying capability is very low as a percentage of installed capacity (less than 10% for the example presented here). This is because of the high probability of having zero available output at time of peak demand, if peak demand occurs on the wrong part of the tidal cycle; this result may be explained transparently using a simple two-state model of the barrage. The prospects for building a probabilistic model of tidal barrage availability are also discussed.

WS3.11 FINLAY, L., INGRAM, D. M. & COUCH, S. J.: “Numerical modelling of tidal resonance in relation to the presence of a tidal energy barrage”, *Proc. Coastlab 10, 28th September – 1st October 2010, Barcelona, Spain.* <http://www.coastlab10.com/>

A tidal energy barrage has been proposed for the Severn Estuary in the South East of England, and despite recent government announcements that financial support for this project will not be immediately forthcoming, it is recognised that this is still an important project if the UK intends to meet its 2020 carbon reduction targets. The Severn Estuary has one of the highest tidal ranges in the world and being a resonant system helps to increase this tidal range. However, this paper examines whether the construction of a tidal energy barrage acts to reduce tidal resonance within this estuary. A simple finite difference model is used to simulate various estuary scenarios and barrage placements in order to see how channel slope and barrage position affects resonance; Preliminary results indicate that tidal amplitude is reduced with the construction of a barrage with a greater decrease in amplitude with the construction of the larger sized barrages.

WS3.12 COUCH, S. J. & JEFFREY, H. F.: “Tidal current energy: Further development of protocols for equitable testing of device performance”, *International Conference on Ocean Energy – ICOE 2010, Bilbao, Spain.* <http://www.icoe2010bilbao.com/ing/index.aspx>

Harnessing and harvesting of sustainable energy resources is a cornerstone endeavour of the 21st Century. These actions are necessary to address climate change issues and enhance national energy supply security. Multiple technologies for the exploitation of tidal current energy are at various stages of the Research, Development, Demonstration and Deployment pathway. These technologies are designed to capture kinetic energy in vigorous tidal flow regimes and convert this energy into electricity. Accurate monitoring and assessment of performance characteristics of the devices under development is necessary to assist in

design progression and proving, and ultimately to enable differentiation between the various devices developed by proponents. This paper details the development and continuing evolution of one approach to the equitable performance assessment of grid-connected tidal current energy technologies.

WS3.13 IYER, A. S., COUCH, S. J., WALLACE, A. R. & HARRISON, G. P.: “Developing Methodologies for Quantifying the Impact of Tidal Current Energy Variability”, *3rd International Conference on Ocean Energy* – ICOE 2010, Bilbao, Spain. <http://www.icoe2010bilbao.com/ing/index.aspx>

This paper presents research being undertaken as part of the EPSRC SuperGen FlexNet consortium to analyse the spatial and temporal behaviour of tidal current resources. The study explores the availability of tidal current energy at a particular location and examines its timing with respect to electricity demand. Actual performance data from a tidal device is not available; therefore a representative hypothetical device is used to simulate electrical generation output from the available tidal resource. The variability of the power generated is compared with realistic demand data and the level of perturbation is calculated. As the study only considers generation output at one location, the importance of aggregation is highlighted. Two scenarios are presented; 10% and 20% penetration of tidal current energy generation in a small network with variability characteristics similar to the UK system demand. Increasing penetration leads to larger power excursions in the system due to the addition of variable generation.

WS3.14 FINLAY, L., INGRAM, D. M. & COUCH, S. J.: “The response of tidal resonance to the presence of a barrage using a two dimensional numerical model”, *3rd International Conference on Ocean Energy* – ICOE 2010, Bilbao, Spain. <http://www.icoe2010bilbao.com/ing/index.aspx>

Tidal energy barrages are an established but controversial option for harnessing the energy held within the rise and fall of the tide. Despite public and political objections, a tidal barrage has long been proposed for the Severn Estuary, UK. In order to ascertain the impact such a structure may potentially have on tidal resonance in the region, a simple two-dimensional model has been employed to simulate tidal flows through a series of estuary scenarios with a variety of domain geometries and bathymetric conditions. This paper will present modelling results which discuss how tidal resonance is altered by various channel characteristics, with/without barrage scenarios and various barrage locations within the Severn Estuary / Bristol Channel.

WS3.15 EASTON, M. C., WOOLF, D. K. & PANS, S.: “An operational hydrodynamic model of a key tidal-energy site: Inner Sound of Stroma, Pentland Firth (Scotland, UK)”, *3rd International Conference on Ocean Energy* – ICOE 2010, Bilbao, Spain. <http://www.icoe2010bilbao.com/ing/index.aspx>

As a result of significant progress towards the delivery of tidal-stream power the industry is moving swiftly towards the deployment of precommercial arrays. Meanwhile important sites, such as the Pentland Firth, are being made available for development. It is now crucial that we consider how the installation of tidal-stream devices will interact with their host environment. Surveying and modelling of the marine system prior to development is a prerequisite to identifying any significant changes associated with tidal energy deployment.

Faced with these challenges, this work focuses on the construction of a high-resolution operational model of the Inner Sound of Stroma, Pentland Firth. Detailed in situ measurements from the Inner Sound are used to ensure that the model can accurately simulate its true dynamics. The model is subsequently modified to simulate an idealised tidal energy fence. Results reveal a significant power potential from the Inner Sound, but with a caveat of severe alterations to the natural tidal currents. However, tidal current changes are less severe when considering more modest levels of power extraction.

WS3.16 NEILL, S. P., LITT, E. J., COUCH, S. J. & DAVIES, A. G.: “The impact of tidal stream turbines on large-scale sediment dynamics”, *Renewable Energy, Volume 34, Issue 12, December 2009, Pages 2803-2812, ISSN 0960-1481, DOI: 10.1016/j.renene.2009.06.015.* <http://www.sciencedirect.com/science/article/pii/S0960148109002882>

Tidal stream turbines are exploited in regions of high tidal currents. Such energy extraction will alter the hydrodynamics of a tidal region, analogous to increasing the bed friction in the region of extraction. In addition, this study demonstrates that energy extracted with respect to tidal asymmetries due to interactions between quarter (M4) and semi-diurnal (M2) currents will have important implications for large-scale sediment dynamics. Model simulations show that energy extracted from regions of strong tidal asymmetry will have a much more pronounced effect on sediment dynamics than energy extracted from regions of tidal symmetry. The results show that energy extracted from regions of strong tidal asymmetry led to a 20% increase in the magnitude of bed level change averaged over the length of a large estuarine system, compared with energy extracted from regions of tidal symmetry. However, regardless of the location of a tidal stream farm within a tidal system, energy extraction reduces the overall magnitude of bed level change in comparison with non-extraction cases. This has practical application to many areas surrounding the UK, including the Irish Sea and the Bristol Channel, that exhibit strong tidal currents suitable for exploitation of the tidal stream resource, but where large variations in tidal asymmetry occur.

WS3.17 HARRISON, M. E., BATTEN, W. M. J., MYERS, L. E. & BAHAJ, A. S.: “Comparison between CFD simulations and experiments for predicting the far wake of horizontal axis tidal turbines”, *IET Renewable Power Generation*, vol. 4, issue 6, (2010), pp. 613–627.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5621011](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5621011)

The actuator disc is a useful method for parameterising a tidal stream turbine in a solution of the Reynolds averaged Navier–Stokes equations. An actuator disc is a region where similar forces are applied to a flow as would be imposed by a turbine. It is useful where large-scale flow characteristics are of interest, such as the far wake, free surface effects, or installation of multi-turbine arrays. This study compares the characteristics of the wake of an actuator disc, modelled using a steady solution to the Reynolds-averaged Navier–Stokes (RANS) simulated equations, with the  $k-\omega$  shear stress transport (SST) turbulence model, to experimental data measured behind discs of various porosities. The results show that the wake of the experimental and modelled discs has similar characteristics; in both model and experiment, velocity in the near wake decreased as thrust coefficient increased. However, the near wake region in the experiment was shorter than simulated in the model because of near wake turbulence. This, combined with lower ambient turbulence levels in the model, meant that the far wake recovered further downstream, while showing similar overall trends in velocity and turbulence intensity.

WS3.18 NEILL, S. P., JORDAN, J. R. & COUCH, S. J.: “Impact of tidal stream turbines on sand bank dynamics”. *Proceeding of World Renewable Energy Congress (WREC)*, 8-13 May 2011, Sweden. <http://pages.bangor.ac.uk/~ucsa03/documents/WREC2011.pdf>

Previous results from one-dimensional model studies have demonstrated that large-scale exploitation of the tidal stream resource could have a significant impact on large-scale sediment dynamics. In this research, we model the impact which such exploitation would have on the dynamics of offshore sand banks. Such banks have an important role in natural coastal protection, since they cause waves to refract and induce wave breaking. As a case study, we examine the Alderney Race, a strait of water between the island of Alderney (Channel Islands) and Cap de la Hague (France). A morphological model is developed, incorporating tidal energy converter (TEC) device operation as a momentum sink in the three-dimensional hydrodynamic module. Through a series of model experiments, we demonstrate the impact which a full-scale (300 MW) TEC array would have on sediment dynamics when sited in the vicinity of headlands and islands. It is important to understand this aspect of the environmental impact of full-scale TEC operation, since headland and island sand banks comprise of readily mobile sediment grain sizes. Therefore, small changes to the tidal regime can have a large effect on the residual sediment transport pathways, and hence sand bank evolution, over the life cycle of a TEC device.

WS3.19 STIVEN, T., COUCH, S. J. & IYER A. S.: “Assessing the impact of ADCP resolution and sampling rate of tidal current energy projects economics”, *IEEE-OES Oceans’11 Conference*. Santander, 6- 11 June, Spain 2011. <http://www.oceans11ieeesantander.org/>

This research examines the impact of accuracy in tidal current energy resource assessment on the likely economics of a tidal array project, ultimately estimating the impact of resource uncertainty on overall lifetime project economics. The analysis utilises field data gathered at 3 key locations at the European

Marine Energy Centre (EMEC) tidal test-site in the Fall of Warness, Orkney. Data analysis techniques appropriate for application to tidal current energy projects are presented and the results obtained interpreted. The widely adopted Matlab code `t_tide` is then used to conduct harmonic analysis of the tidal current velocity data records. The adjacent ADCP records enable analysis of the spatial variability of the tidal resource at the EMEC site. Electricity generation potential and project revenue estimates are generated using simple and clear assumptions regarding typical tidal turbine topology and array layout. The impact of resource uncertainty on the prediction of Annual Energy Production (AEP) of the idealised array is calculated by varying the temporal and spatial resolution of the ADCP data utilised as input to the analysis, and similarly by using various lengths of the measured tidal records. These scenario based predictions are analysed in a simple financial model to examine the effect resource estimate uncertainty has on the projected returns on investment. Overall, the results suggest one clear conclusion: the range of impacts on project economics of uncertainties introduced by the resource estimation process warrant greater investment of time and money by project and technology developers at an early stage of development.

WS3.20 IYER, A. S., COUCH, S. J., HARRISON, G. P. & WALLACE, A. R.: “Phasing of Tidal current energy around the UK and potential contribution to electricity generation”, *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

Tidal current energy has the potential to play a key role in meeting UK renewable energy targets. Although tides are periodic and predictable, there are times when the current velocity even at high energy sites is too low for power generation. However, it has been proposed that a portfolio of diverse sites located around the UK will deliver firm aggregate output due to the relative phasing of the tidal signal around the coast. This paper analyses whether firm tidal power is feasible with ‘first generation’ tidal current generators suitable for relatively shallow water, high velocity sites. This is achieved through development of realistic scenarios. Time-series data for sites identified as high energy are obtained using a combination of sources for the year 2009. Scenarios incorporate constraints relating to assessment of the economically harvestable resource, tidal technology potential and practical limits to energy extraction dictated by environmental response. Spatial availability of appropriate bathymetric conditions are assessed which provides an additional limit on the energy harvesting potential. Finally, the variability of power generation from tidal current energy is compared with the existing variability of UK electricity demand using National Grid data.

WS3.21 BUCHER, R., & COUCH, S. J.: “Adjusting the financial risk of tidal current projects by optimising the ‘installed capacity/capacity factor’-ratio already during the feasibility stage”, *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

For the sustainable exploitation of non-traditional energy resources innovative project assessment concepts and the application of latest technology are required. Due to the complex marine environment, the conceptual design of commercial-scale tidal arrays represents a challenging task. To prepare for factbased investment decisions, the representation of the marine area in a numerical flow model and capacious computer simulations optimising the scheme layout are required. The differing risk/chance preferences and financial capabilities of potential investors can be taken into account by the examination of the ‘installed capacity/capacity factor’-ratio. The project-specific adaptation of the tidal array layout concept and the determination of beneficial system arrangements will support the effective realization of future marine energy projects.

WS3.22 NEILL, S. P., & COUCH, S. J.: “Impact of Tidal Energy Converter (TEC) Array Operation on Sediment Dynamics”, *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

Large-scale exploitation of the tidal stream resource is likely to alter the regional hydrodynamics, but for practical extraction scenarios this effect is generally considered to be very small. However, since sediment transport is proportional to the cube of velocity, relatively small changes in the tidal currents could translate into large changes in the sediment dynamics. Here, we investigate this effect in relation to

two oceanographic processes: tidal asymmetry and headland sand bank maintenance. Both of these processes have major practical significance. Tidal symmetry/asymmetry is responsible for the large-scale long-term distribution of shelf sea sediment. Any tidal energy scheme which has the potential to alter this largescale distribution could affect the supply of sediment feeding into natural coastal defence systems which remove energy from storm waves, such as beaches and offshore sand banks. Headlands are some of the most attractive regions for exploitation of the tidal stream resource. Any tidal energy scheme which could lead to changes in the morphodynamics of the associated headland sand banks could have implications for coastal flooding, due to changes in the wave distribution, including wave refraction and depth induced wave breaking.

WS3.23 HARDING, S., THOMAS, J., POLAGYE, B., RICHMOND, M., DURGESH, V. & BRYDEN, I.G.: “Extreme Value Analysis of Tidal Stream Velocity Perturbations”, *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

This paper presents a statistical extreme value analysis of maximum velocity perturbations from the mean flow speed in a tidal stream. This study was performed using tidal velocity data measured using both an Acoustic Doppler Velocimeter (ADV) and an Acoustic Doppler Current Profiler (ADCP) at the same location which allows for direct comparison of predictions. The extreme value analysis implements a Peak-Over-Threshold method to explore the effect of perturbation length and time scale on the magnitude of a 50-year perturbation.

WS3.24 RADTKE, J., DENT, C. J. & COUCH, S. J.: “Capacity Value of Large Tidal Barrages”, *IEEE Transactions on Power Systems*, vol.26, no.3, pp.1697-1704, August. 2011. DOI: 10.1109/TPWRS.2010.2095433  
<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5676237&isnumber=5958775>

This paper presents the first detailed capacity value calculation for tidal barrage generation, based on modelling of operational modes for the proposed 8-GW Severn Barrage scheme in Great Britain. The key finding is that the effective load carrying capability is very low as a percentage of installed capacity (less than 10% for the example presented here). This is because of the high probability of having zero available output at time of peak demand, if peak demand occurs on the wrong part of the tidal cycle; this result may be explained transparently using a simple two-state model of the barrage. The prospects for building a probabilistic model of tidal barrage availability are also discussed.

WS3.25 BARBOUR, E., & BRYDEN, I.G.: “Energy Storage in Association with Tidal Current Generation Systems”, *Proceedings of the Institution for mechanical engineers, Journal of Power and Energy*, DOI: 10.1177/0957650911399014, 2011. <http://pia.sagepub.com/content/225/4/443.refs>

This article explores the possibility of coupling a tidal current energy converter (TCEC) with an energy storage system. The purpose of this study is two-fold: first, to show that storage can decrease the loss of output from a TCEC, when there are transmission constraints present. Second, to specify the properties of the storage system (efficiency, capacity, input/output power limit, and self-discharge rate) required in order to produce either demand-matching or base-load output from a TCEC. Models of such systems are constructed. These are run over several spring/neap cycles, to determine the time dependence of the whole system. It is shown that a 1.2 MW tidal current energy converter associated with a 1-MWh storage system of modest efficiency can offer significant advantages over the generator working alone.

WS3.26 BRYDEN, I.G.: “Tidal Energy”, *Encyclopedia of Sustainability Science and Technology*, Springer Science+Business Media, 2011 <http://www.springer.com/physics/book/978-0-387-89469-0>

### **Accepted and/or In Press**

WS3.27 NEILL, S. P., JORDAN, J. R. & COUCH, S. J.: “Impact of tidal energy converter (TEC) arrays on dynamics of headland sand banks” *Renewable Energy*, Volume 37, Issue 1, January 2012, Pages 387-397, ISSN 0960-1481, DOI: 10.1016/j.renene.2011.07.003.  
<http://www.sciencedirect.com/science/article/pii/S0960148111003855>



Previous results from one-dimensional model studies have demonstrated that large-scale exploitation of the tidal stream resource could have a significant impact on large-scale sediment dynamics. In this research, we model the impact that such exploitation would have on the dynamics of headland sand banks. Such sand banks, formed by the large eddies generated by strong tidal flow past headlands, have an important role in natural coastal protection, since they cause waves to refract and dissipate energy. Therefore, a tidal energy converter (TEC) array developed in the vicinity of a headland could alter this natural form of coastal protection. Here, we investigate the impact of TEC array operation on idealised headland sand bank formation, followed by a case study, the Alderney Race: a strait of water between the island of Alderney (Channel Islands) and Cap de la Hague (France). This is achieved through the application of a morphological model that incorporates TEC device operation as an additional bed friction source term in the three-dimensional hydrodynamic module. Through a series of model experiments, we demonstrate the impact that a full-scale (300 MW) TEC array would have on sediment dynamics when sited near a headland. This modelling study demonstrates that a 300 MW TEC array located in the vicinity of a headland could lead to a considerable change in the maintenance of headland sand banks over a spring-neap cycle. If the scale of this change is demonstrated to be significant compared to the natural range of inter-annual and inter-seasonal sand bank variability, then developers of TEC arrays would be advised to examine ways in which they could reduce the environmental impacts of TEC arrays sited near headlands. The most obvious of these is to limit the scale of the array, but if we assume that developers wish to exploit the tidal energy resource to its maximum, the alternative is to site the array strategically (within the bounds of economic feasibility) such that it will not interfere with the natural morphodynamics of the headland system.

WS3.28 BAILIE, H., & BRYDEN, I.G.: “Influence of a quadratic Power take off on the behaviour of a self contained inertial referenced Wave energy converter”, *Proceedings of the Institution of Mechanical Engineers, 2011, Part M, Journal of Engineering for the Maritime Environment, in press.* <http://pim.sagepub.com/>

This paper describes a nonlinear Power Take Off (PTO) system within a buoyant, heaving Wave Energy Converter (WEC). The PTO uses the relative velocity between the main structure of the WEC and an inertial referenced mass contained within its outer envelope. The PTO comprises a linear spring and a quadratic damper. In this paper the mathematical principles behind a working time domain simulation of a nonlinear PTO as applied to a relative motion inertial referenced wave energy converter are presented. The principles could, however, be applied to any differential motion system. The resulting numerical simulation is used to investigate the performance of a representative system in irregular waves and the methodology necessary to determine optimal power extraction is discussed and applied. “Optimisation” of the PTO parameters is discussed with respect to limiting the overall relative motion and large accelerations, as indicators of the expected lifetime and the maintenance requirements of the WEC.

#### **WORKSTREAM 4 – Arrays, wakes and near field effects**

WS4.1 SUN, X., CHICK, J. P. & BRYDEN, I.G.: “Laboratory-Scale Simulation of Energy Extraction from Tidal Currents”, *Renewable Energy, vol. 33, issue 6, (2008), pp. 1267–1274. ISSN 0960-1481, DOI: 10.1016/j.renene.2007.06.018.*  
<http://www.sciencedirect.com/science/article/pii/S0960148107002340>

The energy available from tidal currents is substantial and considerable work has been conducted into determining the size of the resource and what the large-scale consequences of extraction might be. This paper describes the work conducted to establish a laboratory-scale model, by using the commercial computational fluid dynamics (CFD) code FLUENT™, in order to predict local-flow consequences resulting from the extraction of energy in two and three dimensions from within the water column in a tidal flow. As might be expected, a wake is formed but there is considerable localized flow acceleration around and, most especially, under an extraction zone. The wake behind the device is shown to be associated with a drop in the free surface which, in turn, is associated with the decline in the wake itself.

WS4.2 FOLLEY, M., SUAREZ, B. P. & WHITTAKER, T.: “An autonomous wave-powered desalination system”, *Desalination, Volume 220, Issues 1-3, 1 March 2008, Pages 412-421, ISSN 0011-*

9164, DOI: 10.1016/j.desal.2007.01.044.

<http://www.sciencedirect.com/science/article/pii/S0011916407006406>

The potential for an autonomous wave-powered desalination system is considered and it is identified that the most promising configuration is a reverse osmosis (RO) plant utilising a pressure exchanger-intensifier for energy recovery. A numerical model of the RO plant with a pressure exchanger-intensifier is developed that shows that a specific energy consumption of less than 2.0 kW h/m<sup>3</sup> over a wide range of sea-water feed conditions, making it particularly suitable for use with a variable power source such as wave energy. A numerical model of the combined wave-power and desalination plant is also developed that shows that it is possible to supply the desalination plant with sea-water directly pressurised by the wave energy converter, eliminating the cost and energy losses associated with converting the energy into electricity and back to pressurised water. For a typical sea-state the specific hydraulic energy consumption of the desalination plant is estimated to be 1.85 kW h/m<sup>3</sup> whilst maintaining a recovery-ratio of less than 25 to 35% to avoid the need for chemical pre-treatment to eliminate scaling problems. It is suggested that the economic potential for wave-powered desalination depends on these energy and cost savings more than compensating for the reduction in membrane life that occurs with variable feed conditions.

WS4.3 BOAKE, C. B., ATCHESON, M., WHITTAKER, T. J. T. & BRYDEN I. G.: “Selection of a Large Model Scale Field Wave and Tidal Test Site in Strangford Lough, UK”, *1st International Conference on SUPERGEN*, April 2009, Hohai University, Nanjing, China.  
<http://www.ukchinanet.com/>

The Supergen 2 consortium has a planned programme of testing of wave and tidal current power array elements at large model scale. These are being conducted at the Portaferry test site in Strangford Lough in Northern Ireland. This paper describes the processes associated with identifying the most appropriate location of the test site, taking into account the scale of the devices under test. This involves establishing the necessary scale resource characteristics in terms of wave and current speeds and then identifying the most appropriate location for the site. A series of field measurements was conducted across a range of candidate sites. The paper will describe and discuss each of these stages and presents some preliminary results from a first device tests at the tidal site.

WS4.4 FOLLEY, M., ELSAESSER, B. & WHITTAKER, T.: “Analysis of the wave energy resource at the European Marine Energy Centre”, *Coasts, Marine Structures and Breakwaters 2009: Adapting to change*. Edinburgh, Scotland, UK, 16-18 September 2009. <http://www.ice-breakwaters.com/>

WS4.5 FOLLEY, M. & WHITTAKER, T. J. T.: “Analysis of the nearshore wave energy resource”, *Renewable Renewable Energy, Volume 34, Issue 7, July 2009, Pages 1709-1715, ISSN 0960-1481*, DOI: 10.1016/j.renene.2009.01.003.  
<http://www.sciencedirect.com/science/article/pii/S0960148109000160>

Earlier studies have indicated that the gross nearshore wave energy resource is significantly smaller than the gross offshore wave energy resource implying that the deployment of wave energy converters in the nearshore is unlikely to be economic. However, it is argued that the gross wave energy resource is not an appropriate measure for determining the productivity of a wave farm and an alternative measure, the exploitable wave energy resource, is proposed. Calculation of a site's potential using the exploitable wave energy resource is considered superior because it accounts for the directional distribution of the incident waves and the wave energy plant rating that limits the power capture in highly energetic sea-states. A third-generation spectral wave model is used to model the wave transformation from deep water to a nearshore site in a water depth of 10 m. It is shown that energy losses result in a reduction of less than 10% of the net incident wave power. Annual wave data for the North Atlantic coast of Scotland is analysed and indicates that whilst the gross wave energy resource has reduced significantly by the 10 m depth contour, the exploitable wave energy resource is reduced by 7 and 22% for the two sites analysed. This limited reduction in exploitable wave energy resource means that for many exposed coasts, nearshore sites offer similar potential for exploitation of the wave energy resource as offshore sites.

- WS4.6 SUN, X., BRYDEN, I. G., JEFFREY, H. F. & FOREHAND D. I. M.: “An experimental survey in the wake of a simulated tidal current turbine”, *Journal of Marine Engineering and Technology (Proceedings of IMarEST Part A)*, issue 12, (2009), pp. 13–22. <http://www.imarest.org/>

This paper presents two experimental test programmes, conducted in a water flow channel and a tow tank respectively, and devised to investigate the wake behind a simulated horizontal axis tidal current turbine. Both sets of experimental results have identified the wake as having a Gaussian-like shape and the wake deficit recovering gradually with distance downstream. Also, although it is not directly representative of real operating conditions, the appropriateness of a towing tank for the model tidal current turbine testing has been supported, by having obtained compatible force and wake profiles in the two test programmes.

- WS4.7 FOLLEY, M. & WHITTAKER, T.: “The effect of sub-optimal control and the spectral wave climate on the performance of wave energy converter arrays”, *Applied Ocean Research*, Volume 31, Issue 4, October 2009, Pages 260-266, ISSN 0141-1187, DOI: 10.1016/j.apor.2009.10.006. <http://www.sciencedirect.com/science/article/pii/S0141118709000947>

A linear hydrodynamic model is used to assess the sensitivity of the performance of a wave energy converter (WEC) array to control parameters. It is found that WEC arrays have a much smaller tolerance to imprecision of the control parameters than isolated WECs and that the increase in power capture of WEC arrays is only achieved with larger amplitudes of motion of the individual WECs. The WEC array radiation pattern is found to provide useful insight into the array hydrodynamics. The linear hydrodynamic model is used, together with the wave climate at the European Marine Energy Centre (EMEC), to assess the maximum annual average power capture of a WEC array. It is found that the maximum annual average power capture is significantly reduced compared to the maximum power capture for regular waves and that the optimum array configuration is also significantly modified. It is concluded that the optimum configuration of a WEC array will be as much influenced by factors such as mooring layout, device access and power smoothing as it is by the theoretical optimum hydrodynamic configuration.

- WS4.8 FOLLEY, M. & WHITTAKER, T.: “The control of wave energy converters using active bipolar damping”, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 223, issue M4, (2009), pp. 479–487. <http://pim.sagepub.com/>

A novel method for controlling wave energy converters using active bipolar damping is described and compared with current control methods. The performance of active bipolar damping is modelled numerically for two distinct types of wave energy converter and it is found that in both cases the power capture can be significantly increased relative to optimal linear damping. It is shown that this is because active bipolar damping has the potential for providing a quasi-spring or quasi-inertia, which improves the wave energy converter's tuning and amplitude of motion, resulting in the increase in power capture observed. The practical implementation of active bipolar damping is also discussed. It is noted that active bipolar damping does not require a reactive energy store and thereby reduces the cost and eliminates losses due to the cycling of reactive energy. It is also noted that active bipolar damping could be implemented using a single constant pressure double-acting hydraulic cylinder and so potentially represents a simple, efficient, robust and economic solution to the control of wave energy converters.

- WS4.9 FOLLEY, M. & WHITTAKER, T.: “The cost of water from an autonomous wave-powered desalination plant”, *Renewable Energy*, Volume 34, Issue 1, January 2009, Pages 75-81, ISSN 0960-1481, DOI: 10.1016/j.renene.2008.03.009. <http://www.sciencedirect.com/science/article/pii/S0960148108000888>

A techno-economic model of an autonomous wave-powered desalination plant is developed and indicates that fresh water can be produced for as little as £0.45/m<sup>3</sup>. The advantages of an autonomous wave-powered desalination plant are also discussed indicating that the real value of the system is enhanced due to its flexibility for deployment and reduced environmental impact. The modelled plant consists of the Oyster wave energy converter, conventional reverse osmosis membranes and a pressure exchanger–intensifier for energy recovery. A time-domain model of the plant is produced using wave-tank

experimentation to calibrate the model of Oyster, manufacturer's data for the model of the reverse osmosis membranes and a hydraulic model of the pressure exchanger-intensifier. The economic model of the plant uses best-estimate cost data which are reduced to annualised costs to facilitate the calculation of the cost of water. Finally, the barriers to the deployment of this technology are discussed, but they are not considered insurmountable.

WS4.10 GRETTON, G. I., BRYDEN, I. G., COUCH, S. J. & INGRAM, D. M.: "The CFD Simulation of a Lifting Hydrofoil in Close Proximity to a Free Surface", *29th International Conference on Ocean, Offshore and Arctic Engineering*, OMAE 2010, Shanghai, Paper # OMAE2010-20936. <http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=ASMECP00201004914900087500001&idtype=cvips&gifs=yes>

This paper presents results from the CFD simulation of a lifting hydrofoil in close proximity to a free surface. The case considered is that of a NACA 0012 hydrofoil at a Froude number of 0.567. The depth of submergence is approximately equal to the chord length. All results were produced using the commercial CFD code ANSYS-CFX. The primary emphasis of this paper is on the detailed and quantitative verification of the CFD simulations, focussing especially on the spatial discretization and the choice of boundary conditions. Quantitative assessment is by examining the free surface deformation and the lift, drag and moment coefficients. It is found that a very fine mesh (having approximately  $1 \times 10^6$  nodes for this 2D case) is required for an accurate prediction of the free surface deformation, whereas a considerably coarser mesh (having approximately  $62 \times 10^3$  nodes) gives comparatively accurate prediction of the lift, drag and moment coefficients.

WS4.11 HARRISON, M. E., BATTEN, W. M. & BAHAI, A.S.: "A blade element actuator disc approach applied to tidal stream turbines." *Proceedings Oceans '10, Seattle, USA*, 20th-23rd September 2010. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5664564>

At a commercial scale tidal stream turbines are likely to be installed in multi-device arrays to maximise power output from a tidal site. This paper demonstrates a computationally efficient method for predicting the performance of an array. The approach parameterises the turbine by deriving momentum source terms using blade element (BE) theory. The source terms are added to Reynolds-averaged Navier-Stokes (RANS) momentum equations. The RANS+BE method is similar to blade element momentum (BEM) theory but can predict the flow field as well as the performance of the rotor. This investigation first verifies the RANS+BE method against BEM theory and shows good agreement, although tip-losses still need to be included. Secondly, it compares the RANS+BE approach to a parameterisation based on a uniform resistance coefficient, over a range of ambient turbulence values and thrust coefficients. The RANS+BE method generates increased azimuthal velocities in the near wake compared to the uniform approach. Finally the investigation compares results of a model of an infinitely wide array of turbines with five rows. The RANS+BE model can predict the performance of each turbine. and shows more rapid wake velocity recovery within the array. The investigation provides a detailed insight into the applicability of wake modelling techniques for the configuration of tidal stream turbine arrays.

WS4.12 ROSE, S., JOHNSTONE, C. & GRANT, A.: "Investigating The Wake Of A Marine Energy Converter Through Flume Channel Testing", *Proceedings of the World Renewable Energy Congress XI*, 27-30 Sept. 2010, Abu Dhabi, UAE. <http://www.wrenuk.co.uk/>

This paper discusses the wake measurements of a small scale model horizontal axis tidal turbine which have been undertaken in the University of Strathclyde's flume channel. The turbine consists of a generic mono-pile mounted device, able to be run in a variety of configurations by changing the Tip Speed Ratio; the measuring device was an Acoustic Doppler Velocimeter. From point measurements a series of wake profiles were constructed, and analysed.

WS4.13 ORDONEZ-SANCHEZ, S., GRANT, A., JOHNSTONE, C. & ROSE, S.: "Experimental Tank Testing of Contra Rotating Marine Turbines to Quantify the Parameters Influencing System Dynamic Response", *Proceedings of the World Renewable Energy Congress XI*, 27-30 Sept. 2010, Abu Dhabi, UAE. <http://www.wrenuk.co.uk/>

Recent in-sea trials have demonstrated the feasibility of utilising contra rotating marine energy converters fixed to the seabed with a flexible mooring. In order to undertake a deeper analysis into the dynamic response of such tethered devices in a controlled and repeatable environment, experiments on scaled rotor devices were carried out in both flume and tow tank facilities at the University of Strathclyde. The tests involved the use of four different configurations of coaxial rotors instrumented with a 3 axis accelerometer, a torque transducer and an axial strain gauge. Within the tow tank tests, towing carriage velocities were in the range of 0.3m/s to 1.6m/s. The results show the influence of rotor blade number on the stability of a contra-rotating turbine. Comparisons between flume and towing tank tests give an indication of the effect of free-stream turbulence on dynamic behaviour. The consequences for the performance of large flexibly moored devices in tidal channels are discussed.

WS4.14 ALEXANDRE, A., STALLARD, T. & STANSBY, P. K.: “Wavefield modifications due to a wave energy converters array”, *Proc. Coastlab 10*, 28th September – 1st October 2010, Barcelona, Spain. <http://www.coastlab10.com/>

As commercial interest in the generation of electricity from wave energy converters (WEC) array increases, it is important to understand how large arrays of converters will interact with the wavefield. This is particularly important at an early stage of the industry development so that costal impacts of future projects can be assessed with confidence. Several studies have been published of the environmental impact of future wave energy arrays but most studies are based on the assumption that energy extraction can be represented by a simple phase-averaged model of energy extraction. These studies neglect the scatter and radiant wavefield and respective phases. Here two approaches for modelling the wave spectrum inshore of a wave device array are compared. The energy spectrum inshore of a device array is estimated considering i) frequency dependant energy reduction and ii) phase-resolving of the wave-field in the vicinity of an array. The diffracted and radiated wave-field is resolved in the vicinity of the array using the potential flow code WAMIT™ such that the combined wave-field is obtained by superimposition. For an equivalent power transmission factor, each method provides a different spectrum inshore of a semi-infinite array. Propagation of these spectra onto a shallow slope shore using SWAN indicates the sensitivity of nearshore conditions of the wave-energy extraction model. Nearshore properties such as significant wave height and spectral shape are predicted and compared to the undisturbed case to quantify the influence of wave energy extraction model on nearshore conditions. For example, the wave breaking height predicted by the two methods differs by 8%.

WS4.15 JOHNSON, P. B., GRETTON, G. I. & MCCOMBES, T.: “Numerical modelling of cross-flow turbines: a direct comparison of four prediction techniques”, *Proceedings of the International Conference in Ocean Energy – ICOE 2010*, 6th – 8th October, 2010, Bilbao, Spain <http://www.icoe2010bilbao.com/ing/index.aspx>

This paper presents a direct comparison of four methods of predicting cross-flow (vertical-axis) tidal stream turbine behaviour. A number of prediction methods are available, and for developers of crossflow turbines it is not always clear, given their requirements, which method is most appropriate.

We compare the four most applicable methods of predicting cross-flow turbine behaviour: the blade element momentum model, the discrete vortex model, a combined boundary element/finite-volume vortex model, and Reynolds-averaged Navier-Stokes simulations. In the present work all of the methods are implemented in two-dimensions in an unbounded flow.

A comparison of the performance of these methods is based primarily on predictions of blade forces on an isolated turbine of 2.5m diameter, with three blades of 0.2m chord and NACA 0024 section.

WS4.16 ORDONEZ-SANCHEZ, S., GRANT, A. & JOHNSTONE, C.: “Contra Rotating Marine Turbines Tank Tests to Analyse System Dynamic Response”, *Proceedings of the International Conference in Ocean Energy – ICOE 2010*, 6th – 8th October, 2010, Bilbao, Spain. <http://www.icoe2010bilbao.com/ing/index.aspx>

Experiments have been undertaken within a repeatable and controlled environment at the University of Strathclyde flume and tow tanks. This was to identify and better understand the influential parameters which dictate how tethered turbines respond in changeable tidal flow conditions.

Two design types of a neutrally buoyant turbine were considered: (i) a contra-rotating turbine consisting of two and three blade rotor configurations, for the upstream and downstream set respectively; and (ii) three and four blade rotor configurations, for upstream and downstream sets respectively. These devices were subjected to towing velocities ranging from 0.5m/s to 1.5 m/s. A mechanical brake controls the torque load of each rotor. The power generated by each turbine configuration when operating in different flow velocities was measured.

This paper thus presents the experimental work undertaken; identifies the individual parameters impacting upon turbine stability when supported by a flexible mooring; reports and discusses device performance, dynamic response and thrust forces; and comments on the ability to balance the reactive torque for different configurations of contra rotating rotors. The paper concludes by showing the differences in turbine performance and stability for each configuration by applying a torque control strategy.

WS4.17 RAWLINSON-SMITH, R., BRYDEN, I., FOLLEY, M., MARTIN, V., STALLARD, T., STOCK-WILLIAMS, C. & WILLDEN, R.: “The PerAWaT project: Performance Assessment of Wave and Tidal Array Systems.” *Proceedings of the International Conference in Ocean Energy – ICOE 2010*, 6th – 8th October, 2010, Bilbao, Spain <http://www.icoe2010bilbao.com/ing/index.aspx>

The Energy Technologies Institute (ETI) is a UK based company formed from global industrial companies and the UK government. The ETI invests in projects to help create affordable, reliable, clean energy for heat, power and transport. The ETI core objective of accelerating the development and commercial deployment of energy technologies that reduce greenhouse gas emissions and help to achieve energy and climate change goals will be addressed by the primary objective of the PerAWaT project which is: To establish and validate numerical models to predict the hydrodynamic performance of wave & tidal energy converters operating in arrays. The deployment of large scale arrays of wave and tidal energy conversion devices will only occur when project developers have sufficient confidence in the return on their investment. This requires proven prototypes and validated methods for the prediction of resource and energy capture. This paper provides an overview of the PerAWaT project which will build on existing knowledge to accelerate the development of sophisticated tools that will become essential as the wave and tidal energy industries mature.

WS4.18 VENUGOPAL, V., BRYDEN, I. G., WALLACE, A. R.: “On the Interaction of Waves with an Array of Open Chambered Structures: Application to Wave Energy Converters”, *Proceedings of 29th International Conference on Offshore Mechanics and Arctic Engineering, OMAE 2010, Paper 20300, Shanghai, China*  
<http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=ASMECP00201004911800036500001&idtype=cvips&gifs=yes>

The results of a study carried out to determine the modification of wave climate around an array of open chambered structures, which could represent an array of wave power devices are presented in this paper. The wave-structure interaction is studied using the Boussinesq wave model within the MIKE 21 suite software. The spacing between two adjacent structures within the array is varied from 1S to 5S, where S is equal to 20 m. The effect of varying the spacing between individual structures and the resulting wave reflection and transmission around the array is illustrated using simulated random waves. The results show that the degree of reflection and transmission mainly depends on the spacing between individual structures and the peak wave periods. The maximum increase in significant wave height due to wave reflection in front of the array reached about 39% and the maximum reduction in significant wave height downstream the array is found to be about 41%. The results presented in this paper should be of interest to the wave energy industry.

WS4.19 FOLLEY, M. & WHITTAKER, T.: “Spectral modelling of wave energy converters”, *Coastal Engineering, Volume 57, Issue 10, October 2010, Pages 892-897, ISSN 0378-3839, DOI:*

10.1016/j.coastaleng.2010.05.007.

<http://www.sciencedirect.com/science/article/pii/S0378383910000700>

A spectral model suitable for the representation of wave energy converters is developed. A spectral model is an extension of a frequency-domain model that allows inclusion of non-linear forces and thereby provides improved estimates of wave energy converter performance, without the high computational cost of a time-domain model. The suitability and accuracy of a spectral model representation is demonstrated for a flap-type wave energy converter, by modelling the effect of vortex shedding and large amplitudes of motion. The development of a spectral model of wave energy converters also means that they can be represented in spectral wave models and included explicitly in software tools such as SWAN or Mike21 SW. This means that tools familiar to the industry could be used to determine the environmental impact and energy yield of wave farms efficiently.

WS4.20 CHILD, B. F. M. & VENUGOPAL, V.: “Optimal configurations of wave energy device arrays”, *Ocean Engineering, Volume 37, Issue 16, November 2010, Pages 1402-1417, ISSN 0029-8018*, DOI: 10.1016/j.oceaneng.2010.06.010.

<http://www.sciencedirect.com/science/article/pii/S0029801810001447>

In this paper, the influence of the spatial configuration of a wave energy device array upon total power output is investigated. Hydrodynamic interactions are computed using a method capable of producing the linear wave theory solution to arbitrary accuracy. The overall performance of devices with two different power take-off arrangements is maximised at one incident wave frequency and direction by altering the formation of the array. Minimisation of the power is also carried out in a third case in order to demonstrate potential array-related losses. The optimisation is applied using two different approaches in each case: the Parabolic Intersection (PI) method and a Genetic Algorithm (GA). The former is a heuristic technique that has been devised for this study to enable rapid array construction using only simple calculations. The latter is an existing method, applied here with a novel crossover operator. Although considerably more computational effort is required, superior results may be obtained using the GA compared to the PI method. All of the arrays are subsequently analysed under incident waves of different frequency and direction, the resulting behaviour explained in terms of certain geometrical features of the arrangements.

WS4.21 HARRISON, M. E., BATTEN, W. M. J., MYERS, L. E. & BAHAJ, A. S.: “Comparison between CFD simulations and experiments for predicting the far wake of horizontal axis tidal turbines”, *Renewable Power Generation, IET, vol.4, no.6, pp.613-627, November 2010*. DOI: 10.1049/iet-rpg.2009.0193. [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5621011](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5621011)

The actuator disc is a useful method for parameterising a tidal stream turbine in a solution of the Reynolds-averaged Navier-Stokes equations. An actuator disc is a region where similar forces are applied to a flow as would be imposed by a turbine. It is useful where large-scale flow characteristics are of interest, such as the far wake, free surface effects, or installation of multi-turbine arrays. This study compares the characteristics of the wake of an actuator disc, modelled using a steady solution to the Reynolds-averaged Navier-Stokes (RANS) simulated equations, with the  $k$ - $\epsilon$  shear stress transport (SST) turbulence model, to experimental data measured behind discs of various porosities. The results show that the wake of the experimental and modelled discs has similar characteristics; in both model and experiment, velocity in the near wake decreased as thrust coefficient increased. However, the near wake region in the experiment was shorter than simulated in the model because of near wake turbulence. This, combined with lower ambient turbulence levels in the model, meant that the far wake recovered further downstream, while showing similar overall trends in velocity and turbulence intensity.

WS4.22 ROSE, S., ORDONEZ-SANCHEZ, S., LEE, K.H., JOHNSTONE, C., JO, C.H., MCCOMBES, T., & GRANT, A.: “Tidal Turbine Wakes: a Comparison between Small Scale Experimental and Computational Results.” *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

This paper seeks to present experimental wake characterisation carried out in the Faculty of Engineering circulating flume tank at the University of Strathclyde, and offer a preliminary comparison with this and a

numerical simulation using Computational Fluid Dynamics (CFD) carried out at Inha University. The research focuses on the investigation of the undisturbed flow behind a single rotor marine turbine of 0.3 m rotor diameter, specifically examining the velocity deficit and turbulence intensity. Two configurations were used: a 2 bladed rotor, and a 3 bladed rotor. Velocity measurements were acquired for a variation of pitching angles using an Acoustic Doppler Velocimeter (ADV). A computational model capable of replication is then discussed, using a commercial CFD package, and defining the tip speed ratio and the boundary conditions as measured in the tank tests.

WS4.23 ROSE, S., GOOD, A., ATCHESON, M., HAMILL, G., JOHNSTONE, C., MACKINNON, P., ROBINSON, D., GRANT, A & WHITTAKER, T.: "Investigating Experimental Techniques for Measurement of the Downstream Near Wake of a Tidal Turbine." *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

A number of experimental techniques have been applied in order to measure the velocity and turbulence characteristics of the downstream wake of horizontal axis tidal turbine models at various scales. This paper describes three such experiments undertaken at Queen's University Belfast and the University of Strathclyde. Data from each of the experiments are presented and discussed. The advantages and disadvantages of the two data capture methods (Acoustic Doppler Velocimetry or ADV, and particle image velocimetry or PIV) are mentioned, drawing attention to the suitability of each method for certain purposes.

WS4.24 FOLLEY, M. & WHITTAKER, T.: "Validating a spectral domain model of an OWC using physical model data." *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

It has recently been demonstrated that spectral-domain models of wave energy converters (WECs) can provide an accurate and numerically efficient method for predicting the expected performance of WECs. An oscillating water column (OWC) type WEC has been tested in a wave tank to produce validation data for a spectral-domain model of the OWC. The OWC spectral-domain model consists of linear hydrodynamic coefficients obtained from the commercial boundary-element code WAMIT, together with single-coefficient non-linear term for the power-take-off (PTO) and the entry/exit losses of the water column. The OWC was tested in a range of representative sea-states with both unimodal and bimodal spectra. The coefficients for the PTO and entry/exit losses were determined heuristically. Comparison of the OWC spectral-domain model with the wave-tank data indicates that the spectral-domain model reproduces the performance of the OWC accurately. The error in spectral model's prediction of power capture is typically less than 10%. The frequency response of the OWC is also well predicted by the spectral-domain model. This demonstrates that a spectral-domain model provides a valid representation of the wave-tank OWC model performance.

WS4.25 O'BOYLE, L., ELSAESSER, B., FOLLEY, M. & WHITTAKER, T.: "Assessment of Wave Basin Homogeneity for Wave Energy Converter Array Studies." *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

Consideration of wave basin performance is an essential first step to allow extraction of the effect of a wave energy converter (WEC) on wave climate from experimental data. This paper details a combined physical and numerical modelling approach for the assessment of wave basin homogeneity. Physically, this has been done through mapping of the wave climate within a new wave basin in Portaferry, N. Ireland, designed for WEC array studies. The objective being to accurately identify each wave component generated by the wave paddles and the spatial variation due to phase-locking of reflected waves. A Boussinesq model has also been developed as a tool for assessment of wave basin performance and validated using physical results.

The paper explores the implications of these findings on WEC array modelling. Consideration is given to the sensitivity of physical test results to location of point measurements. This leads to a discussion on the



certainty with which device performance and array interactions can be predicted using physical and numerical modelling techniques.

WS4.26 TIETJE, D., FOLLEY, M., BEATTY, S., RAFTERY, M., & RICCI, P.: “Standardised Performance Assessment of Wave Energy Converters.” *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

The industrial development of Wave Energy Converters (WECs) is entering a critical transition from preliminary design to commercial production. Several developers have engaged with electrical utilities to connect to power grids for testing. At such a critical time, efforts to improve transparency such as technical standardization are important for the health of the industry. To this end, the International Electrotechnical Commission (IEC) has established Technical Committee (TC) 114 — a standards development effort for the Marine Hydrokinetic (MHK) industry — which currently addresses the technical aspects of tidal, wave, and other marine current device projects. The deliverables of the TC114 are technical specifications that are currently under development and review. Approval by the IEC of a Technical Specification (TS) provides the option for the TS to become an IEC standard, but does not guarantee the TS will become a standard. TC 114 formed a Project Team (PT) for the performance assessment of WECs.

The goal of the PT, as outlined in this paper, is to develop a specification for the equitable power performance assessment of WECs that will be adaptable as the industry evolves.

WS4.27 PASCAL, R., & BRYDEN, I.G., “Directional Spectrum Methods for Deterministic Waves”, *Ocean Engineering, Volume 38, Issue 13, September 2011, Pages 1382-1396, ISSN 0029-8018*. DOI: 10.1016/j.oceaneng.2011.05.021. <http://www.sciencedirect.com/science/article/pii/S0029801811001119>

This work discusses developments related to the generation and measurement of directional wave spectra in multi-directional wave tank using deterministic waves. The details of the generation method, based on the single summation method described by Jefferys (1987), are given and the capacity of the Edinburgh curved wave tank to generate such waves is assessed. The Maximum Likelihood Method (MLM) and one of its derivative, The Modified Maximum Likelihood Method (MMLM) (Isobe and Kondo, 1985), are adapted to the characteristics of deterministic waves. The methods are assessed both with simulated waves and real wave elevations from the Edinburgh curved tank. Both methods show very satisfactory results with very stable angular spreading estimates and good tracking of mean directions of propagation across frequencies. The adapted MLM compares favourably with the industry standard, the Bayesian Directional Method, while only taking a fraction of the time needed to the BDM to produce its spectral estimates. Keywords: Deterministic waves; Wave tank; Directional spectrum; MLM; MMLM; Wave system isolation

WS4.28 DOHERTY, K., FOLLEY, M., DOHERTY, R., & WHITTAKER, T.: “Extreme Value Analysis of Wave Energy Converters.” 21<sup>st</sup> International Conference on Ocean and Polar Engineering, ISOPE, Maui, Hawaii, USA, June-19-24, 2011. <http://www.aquamarinepower.com/sites/resources/Reports/2920/Extreme%20Value%20Analysis%20of%20Wave%20Energy%20Converters.pdf>

This paper presents a statistical Extreme Value Analysis (EVA) methodology to evaluate the design survivability condition of a Wave Energy Converter (WEC). The technique is applied to the Oyster® WEC design which is being developed by Aquamarine Power Ltd. (APL) but can be easily modified to investigate other technologies that have different operational philosophies. The approach presented considers the extreme statistics of both the incident wave climate at the device location and the complex dynamic response of the WEC in such conditions. This give a more robust evaluation of the WECs survivability condition than a more traditional single design wave approach.

<b>WORKSTREAM 5 - Power take-off and conditioning</b>
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- WS5.1 MUELLER, M.A., McDONALD, A.S., OCHIJE, K. & JEFFREY, J.: “A Novel Permanent Magnet Generator For Direct Drive Wave Energy Applications”, *Proc 7<sup>th</sup> European Wave and Tidal Energy Conference*, Porto, Portugal, September. 2007 [www.ewtec2007.com.pt/](http://www.ewtec2007.com.pt/)

The evolution of a novel permanent magnet (PM) generator topology is described in the paper. It has the significant potential to be lighter than conventional PM machine topologies, making it attractive for direct drive applications in wind, wave and tidal current generators. The philosophy of the generator concept is based upon reducing the structural mass by eliminating large unwanted magnetic attraction forces that exist in all conventional iron-cored electrical machines. A comparison with an existing commercially available rotary PM generator for a 100kW turbine is presented to show the potential of the new topology.

- WS5.2 SHEK, J.K., MACPHERSON, D.E., MUELLER, M.A. & XIANG, J.: “Reaction Force Control of a Linear Electrical Generator for Direct Drive Wave Energy Conversion”, *IET Journal of Renewable Energy*, Vol. 1, March 2007 (224 downloads from IET website, ranked 10<sup>th</sup> of all papers in IET RPG)  
<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4159951&userType=&tag=1>

Direct drive wave energy converters have been proposed in view of the disadvantage of mechanical complexity and low conversion efficiencies in conventional wave energy converters. By directly coupling a linear generator to a reciprocating wave energy device, it is suggested that direct drive power take-off could be a viable alternative to hydraulic- and pneumatic-based systems. To further realise the benefits of a direct drive system, a control scheme based on reaction force control to maximise energy extraction is presented. It focuses predominantly on the theoretical analysis of the linear generator reaction force. The modelling, simulation and control of direct drive wave energy conversion are systematically investigated by computer-aided analysis via Matlab/Simulink.

- WS5.3 MUELLER, M. A., BAKER, N., RAN, L., CHONG, N., WEI, H., TAVNER, P. & MCKEEVER, P.: “Experimental tests of an air-cored PM tubular generator for direct drive wave energy converters”, *Proc 4th IET PEMD Conference*, York, UK, April 2008.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=4528938](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4528938)

Direct drive power take off eliminates the need for a mechanical interface to match the low speed reciprocating motion of a wave device to high speed rotational motion of conventional electrical generators. However, direct drive generators are physically large and heavy due to the low velocities encountered. Iron cored PM machines suffer from magnetic attraction forces which is challenging for the structural and bearing design. An air-cored machine solves the issue of magnetic attraction forces, which will benefit the mechanical design. The performance of an air-cored PM tubular machine is investigated in this paper under displacements typical of a wave energy device.

- WS5.4 HODGINS, N., MUELLER, M. A., TEASE, K. & HEATH, T.: “Measurement and Modelling of Induction Generator Performance in an Oscillating Water Column Wave Energy Converter”, *Proc 4th IET PEMD Conference*, York, UK, April 2008.  
<http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=IEECPS0020080CP538000076000001&idtype=cvips&gifs=yes&ref=no>

A study has been made on power takeoff from an oscillating water column wave energy device. An induction generator can be overloaded to meet peak powers. The maximum overload of an induction generator is limited by internal temperature which is determined by the cooling ability of its environment and the induction generator losses. Measurements of the cooling present in an OWC and its effects on the induction generator temperatures are detailed. A thermal modelling is carried out in MotorCAD and used to extend the measurements.

- WS5.5 SHEK, J.K., MACPHERSON, D.E. & MUELLER, M.A.: “Phase and amplitude control of a linear generator for wave energy conversion”, *Proc 4<sup>th</sup> IET PEMD Conference*, York, April 2008.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?tp=&arnumber=4528801](http://ieeexplore.ieee.org/xpls/abs_all.jsp?tp=&arnumber=4528801)

Direct drive power take-off for wave energy conversion has been proposed as a viable alternative to hydraulic and pneumatic based systems found in conventional wave energy converters. Allowing for further benefits to be realised, this paper presents a reaction force control scheme to maximise energy extraction, and investigates the modelling and simulation of a direct drive wave energy converter. The control scheme is applied to an experimental test rig with a prototype linear machine with results presented and analysed.

- WS5.6 MCDONALD, A., MUELLER, M. A., JEFFREY, J. & OCHIJE, K.: “Development Of A Novel Permanent Magnet Linear Generator Topology For Direct-Drive Wave Energy Converters”, *Proceedings of the 4th IET PEMD Conference*, York, UK, April 2008.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=4528804](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4528804)

A new permanent magnet linear machine uses an air-cored winding and a new translator module structure to overcome the normal attraction between stator and translator. The 'C' core module is analysed both magnetically and structurally. Assembly procedure is described and results from a small prototype machine are given.

- WS5.7 CARAHER, S., CHICK, J. & MUELLER, M. A.: “Investigation of Fluid Film Bearings for use in Direct Drive Linear Generators in submerged wave energy converters”, *presented at ISOPE*, Vancouver, 2008.  
<http://www.isopec.org/publications/proceedings/ISOPE/ISOPE%202008/papers/108TPC-131Cara.pdf>

Many difficulties face the operation of offshore wave energy converters. If a structure is to survive and work effectively with little maintenance the unpredictable, harsh, corrosive environment provides many design challenges. For a double sided iron cored permanent magnet linear synchronous generator in a direct drive system, the difficulties increase. High normal forces exert a strong attractive clamping force between the stator and translator that the machines' bearings must react against. The normal forces are 10 to 20 times higher than the generators shear forces. The design of novel fluid film linear bearings for such a generator is the subject of this paper.

- WS5.8 CROZIER, R. & MUELLER, M. A.: “Modelling and First Order Optimisation of the Air-Cored Tubular PM Machine Using Polynomial Approximation”, *Proceedings of the International Conference on Electrical Machines*, Portugal, 2008.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=4800133](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4800133)

Finite element analysis remains the most reliable method of simulating electromagnetic systems. When attempting to optimise a system, FEA can be computationally expensive and time consuming. This paper demonstrates the use of polynomial approximation to FEA results to minimise the necessary number of FEA simulations. Using this method, a simulation is developed, capable of accurately reproducing the magnetic field above one pole in the air-cored tubular permanent magnet machine for any combination of machine parameters in a pre-chosen design space. The same method is also employed to optimise the machine parameters to produce the maximum reaction force for a fixed current. A second optimisation is also presented based on the capital cost per average power produced per unit length of translator in a typical wave motion.

- WS5.9 CARAHER, S., CHICK, J. & MUELLER, M. A.: “Investigation into Hydrostatic and Contact Bearings for use in Direct Drive Linear Generators in Submerged Wave Energy Converters”, *Proceedings of the International Conference on Ocean Energy*, Brest, France, October 2008.  
<http://www.icoe2008.com/>

The design of a bearing system for a linear generator within a submerged wave energy converter will be based on survivability and low maintenance needs. Optimising these electrical generators involves finding materials and adapting construction to suit their environment without compromising efficiency. Therefore integrating the bearing systems to run reliably and at a low power demand will also require adaptations. This requirement will ultimately be scaled in terms of cost: cost of downtime, cost of replacement, cost of maintenance.

Research into commercial marine bearings shows we have the materials for operation in these harsh conditions. Using a hydrostatic bearing within the generator could be advantageous but the running clearances are extremely small. The machining methods employed to provide them would greatly increase the production cost. Maintaining such clearances over 10m of translator also poses problems. This work aims to combine the use of water suitable materials within contact bearing designs specifically for an offshore direct drive linear generator. Comparisons are made between these contact bearings and water fed hydrostatic bearings.

WS5.10 MUELLER, M. A. & McDONALD, A.: “A lightweight PM generator for direct drive system in marine renewables”, *Proceedings of the International Conference on Ocean Energy*, Brest, France, October 2008. <http://www.icoe2008.com/>

A new type of air-cored permanent magnet generator – known as the “C-GEN” – is introduced. For both linear and rotary types this machine removes the normal component of Maxwell stress between the stator and the moving part of the generator. By eliminating the magnetic attraction forces, the assembly process is easier than for conventional machines. The performance matches that of conventional PM machines but has the potential to scale up to large power levels without the need for large supporting structures.

WS5.11 McDONALD, A., HODGINS, N. W., CROZIER, R. & MUELLER, M. A.: “Integrated Design of Electrical PTO in Marine Renewable Energy Applications”, *Proceedings of the International Conference on Ocean Energy*, Brest, France, October 2008. <http://www.icoe2008.com/>

Examples of integrated design of electrical generators for wave and tidal energy converters are presented. These demonstrate the importance of modelling structural and thermal aspects alongside traditional electromagnetic models. Overall generator production per unit cost can be increased as a result.

WS5.12 MUELLER, M. A. & WALLACE, R.: “Enabling science and technology for marine renewable energy”, *Energy Policy*, Volume 36, Issue 12, December 2008, Pages 4376-4382, ISSN 0301-4215, DOI: 10.1016/j.enpol.2008.09.035. <http://www.sciencedirect.com/science/article/pii/S0301421508004539>

This paper describes some of the key challenges to be met in the development of marine renewable energy technology, from its present prototype form to being a widely deployed contributor to future energy supply. Since 2000, a number of large-scale wave and tidal current prototypes have been demonstrated around the world, but marine renewable energy technology is still 10–15 years behind that of wind energy. UK-based developers are leading the way, with Pelamis from Pelamis Wave Power demonstrated in the open sea, generating electricity into the UK network and securing orders from Portugal. However, having started later, the developing technology can make use of more advanced science and engineering, and it is therefore reasonable to expect rapid progress. Although progress is underway through deployment and testing, there are still key scientific challenges to be addressed in areas including resource assessment and predictability, engineering design and manufacturability, installation, operation and maintenance, survivability, reliability and cost reduction. The research priorities required to meet these challenges are suggested in this paper and have been drawn from current roadmaps and vision documents, including more recent consultations within the community by the UK Energy Research Centre Marine Research Network. Many scientific advances are required to meet these challenges, and their likelihood is explored based on current and future capabilities.

WS5.13 BOGLIETTI, A., CAVAGNINO, A., STATON, D., SHANEL, M., MUELLER, M. & MEJUTO, C.: “Evolution and modern approaches for thermal analysis of electrical machines”, *Industrial Electronics, IEEE Transactions on*, vol.56, no.3, pp.871-882, March 2009 DOI: 10.1109/TIE.2008.2011622 [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=4796880](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4796880)

In this paper, the authors present an extended survey on the evolution and the modern approaches in the thermal analysis of electrical machines. The improvements and the new techniques proposed in the last decade are analyzed in depth and compared in order to highlight the qualities and defects of each. In particular, thermal analysis based on lumped-parameter thermal network, finite-element analysis, and

computational fluid dynamics are considered in this paper. In addition, an overview of the problems linked to the thermal parameter determination and computation is proposed and discussed. Taking into account the aims of this paper, a detailed list of books and papers is reported in the references to help researchers interested in these topics.

- WS5.14 CARAHER, S. L., CROZIER, R., MCDONALD, A. S., MUELLER, M. A. & CHICK, J. P.: “Integrated structural and electrical design of the linear permanent magnet synchronous machine”, *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/>

Linear permanent magnet generators are a potentially useful technology for wave power applications. Typically, optimisation and comparison of these generators is based on an electromagnetic analysis with limited regard for the structural analysis. This paper presents a comparison of two alternative designs of the double-sided linear permanent magnet synchronous machine which includes structural and bearing requirements for a more accurate assessment of cost and feasibility. It is shown that both cost and feasibility depend heavily on these issues due to the large internal and external forces acting on the machine.

- WS5.15 FLETCHER, J., JUDENDORFER, T., MUELLER, M., HASSANAIN, N. & MUHR, M.: “Electrical issues associated with sea-water immersed windings in electrical generators for wave- and tidal current-driven power generation”, *Renewable Power Generation, IET*, vol.3, no.2, pp.254-264, June 2009 DOI: 10.1049/iet-rpg:20080083 [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=4957259](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4957259)

For the majority of proposed wave- and tidal current-driven power generation applications, the electrical generators are submerged in sea water, frequently at many metres of depth. The environment places significant stress on the rotating or translating seals between the driven shaft and the electrical generator leading to reduced reliability and lifetime. A potential solution is to eliminate the seal, thereby flooding the generator and allowing sea water to circulate around the shaft, windings and rotor of the machine. The impact of immersing the windings of the machine in sea water is assessed here. Specifically, the impact that the insulation has on the leakage capacitance as well as the consequent impact the leakage capacitance has on current and voltage oscillations in the switching converter used to excite the winding is assessed. Thermal tests are conducted to assess the impact of the insulation on the thermal conductance of the coil-insulation system. Experimental evidence is provided.

- WS5.16 HODGINS, N., MCDONALD, A. S., SHEK, J., KEYSAN, O. & MUELLER, M.: “Current and future developments of the C-GEN lightweight direct drive generator for wave and tidal energy”, *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/>

The C-GEN is a novel permanent magnet generator aimed at reducing overall system mass in direct drive power takeoff applications. The design of a C-GEN generator requires the combination of electromagnetic, structural and thermal models. Two rotary prototypes of 15 & 20kW have been constructed and tested and the 15kW prototype has been fitted to a wind turbine. A 1kW linear generator has been tested and is being modified for flooded operation meanwhile a larger 50kW prototype is being designed. A feasibility study of C-GEN technology in four different wave and tidal projects is being undertaken.

- WS5.17 MCDONALD, A. S., CROZIER, R., CARAHER, S. L., CHICK, J. P. & MUELLER, M.: “Integrated design of direct drive generators for wave energy converters”, *The 1st International Conference on Sustainable Power Generation and Supply (SuperGen)*, Nanjing, China, 6-7 April 2009. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5348025>

Linear permanent magnet generators are a potentially useful technology for wave power applications. Typically, optimisation and comparison of these generators is based on an electromagnetic analysis with limited regard for the structural and thermal analysis. This paper presents a comparison of an air-cored synchronous machine and a double-sided iron-cored synchronous machine which includes the structural

and bearing requirements for a more accurate cost comparison, and a discussion of the thermal issues. It is shown that both cost and feasibility depend heavily on these issues.

- WS5.18 KEYSAN, O., MCDONALD, A.S., MUELLER, M.A., DOHERTY, R. & HAMILTON, M.: “C-gen, a lightweight direct drive generator for marine energy converters”, *Proc IET Power Electronics Machines & Drives Conference*, Brighton, April 2010.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5523799](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5523799)

C-GEN is a new topology of direct-drive permanent magnet generator being developed at University of Edinburgh. The main benefits are reduced overall system mass and ease of manufacturing, due to the use of an air-cored winding, but with a modular PM rotor consisting of C-core modules. A 15kW rotary prototype has been fitted and tested on a commercially available wind turbine. Initial sizing studies for wind indicate that the C-GEN concept will be up to 50% lighter than conventional iron cored PM direct drive generators [10]. In addition to wind the C-GEN has applications in marine energy converters. The authors are working with four marine developers to investigate the feasibility of C-GEN for their technology. The results from two of those studies will be presented in this paper namely; Aquamarine Oyster device - near shore wave energy converter, Scotrenewables SRTT device - tidal current energy converter. In order to find the most optimum solution for the specific application; electromagnetic, thermal, structural and economical design aspects of the generator are defined and coupled using an analytical design tool. To evaluate different design variations an optimization tool is developed based on genetic algorithm. All these considerations make the optimised generator design a very close optimum solution for the “real-world”.

- WS5.19 SHEK, J. K. H., MACPHERSON, D. E. & MUELLER, M. A.: “Power Conversion for Wave Energy Applications”, *IET International Conference on Power Electronics, Machines, and Drives – PEMD 2010*. [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5523801](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5523801)

Wave energy converters require a power conversion stage to convert the variable output from an electrical generator into a constant voltage and frequency for grid connection. To enable further development in grid integration of wave energy converter systems, this paper looks at the main power conversion considerations in converting wave energy into electrical energy and reviews current power converter topologies. In particular, the paper highlights the trade-off between energy storage, which brings about improved power quality, and improved reliability due to the absence of capacitors.

- WS5.20 CARAHER, S., CHICK, J. P., MUELLER, M. A., STEYNOR, J. & STRATFORD, T.: “Test Rig Design and Development for Linear Bearings in Direct Drive Generators”, *3rd International Conference on Ocean Energy*; 6-8 October; Bilbao, Spain; 2010.  
<http://www.icoe2010bilbao.com/ing/index.aspx>

To be financially viable, both avoiding excessive downtime and offering continued power generation, the design of a submerged wave energy converter (WEC) must be based around survivability and low maintenance needs. A direct drive linear generator as the power take off (PTO) in a WEC has significant potential advantages towards this through i) efficiency, operating with matched speed to the device’s source of motion whether it is a wind, wave or tidal device, ii) low risk, with reduced number of components in comparison to hydraulic or mechanical systems, and iii) cost effectiveness, lower mass and material cost is achieved from an integrated design approach. A crucial part of the linear generator’s reliability is the performance of its’ bearings. This work explores how plain contact polymer linear bearings react when tested under conditions that replicate their operation in a WEC. The content of this paper focuses on the work involved in converting a prototype novel linear generator, the C-Gen machine, into a test rig to determine response of the bearings to submerged, loaded, oscillating operation.

- WS5.21 CROZIER, R., BAILEY, H., MUELLER, M.A., SPOONER, E. & MCKEEVER, P, “Hydrodynamic and Electromechanical Simulation of a Snapper Based Wave Energy Converter”, *Proc. IEEE IECON conference*, Arizona, November 2010.  
<http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05674966>

A coupled electromechanical and hydrodynamic simulation of a novel generator connected to a heaving buoy for wave energy conversion has been developed. The simulation is based primarily in MATLAB using its built-in Ordinary Differential Equation (ODE) solvers. These solvers have acted on the data derived from an electromagnetic finite element analysis and from the WAMIT wave interaction simulation software, to simulate the full system in the time domain.

WS5.22 HODGINS, N., MUELLER, M.A., TEASE, W.K. & STATON, D.: “Thermal model of an induction generator in oscillating water column wave energy converter”, *Proc IET Power Electronics Machines & Drives Conference*, Brighton, April 2010.  
<http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05523798>

A thermal model for an induction generator in a renewable energy application is presented. The thermal resistances used in the model are found from steady state testing in an appropriate environment. The cooling in this application is inherently better than that normally experienced by this type of generator and thus a rating above nameplate can be achieved continuously.

WS5.23 KEYSAN, O., HODGINS, N., McDONALD, A.S., SHEK, J.K & MUELLER, M.A.: “Linear Generator for Direct Drive Wave Energy Applications”, *Proc International Conference on Electrical Machines*, Rome, September 2010 - AWARDED BEST PAPER.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5607840](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5607840)

A 50kW linear permanent magnet generator with a novel topology has been designed and built. The main significance of the generator topology is that there is no attractive force between the stator and permanent magnet translator. The magnetic force between the magnets is reacted within a self supporting structure. The lack of magnetic forces closing the airgap and the modular nature of the generator topology makes the manufacture and assembly of the generator easier than a conventional iron-cored permanent magnet linear generator. Photos of the manufacturing process are included in this paper. The modelling techniques used to design the generator are described and a summary of the design is presented.

WS5.24 SHEK, J. K. H., MACPHERSON, D. E. & MUELLER, M. A.: “Experimental verification of linear generator control for direct drive wave energy conversion”, *IET Renewable Power Generation*, vol. 4, issue 5, (2010), pp. 395–403.  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5559313](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5559313)

It has been shown through modelling and simulation that a linear electrical generator can be effectively controlled to maximise the energy extracted from sea waves. A reaction force control scheme allows the performance of a direct drive wave energy converter to be optimised, which adds to the benefits of low mechanical complexity and high conversion efficiencies in a direct drive system. In this study, reaction force control through experimental verification is presented. The use of a linear generator test rig and electronic hardware to control the phase and amplitude of oscillation are investigated.

WS5.25 KEYSAN, O. & MUELLER, M.A.: “A Direct Drive Permanent Magnet Generator Design for a Tidal Current Turbine (SeaGen)”, *IEEE IEMDC Conference*, Niagara, May 2011 (*Best Poster Award*) [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5994850](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5994850)

In this study, the feasibility of a direct-drive permanent magnet generator for a tidal turbine power take-off system, namely MCTs SeaGen the worlds first full scale commercial tidal turbine has been investigated. The investigated PM generator topology is called C-GEN which is an air-cored axial-flux generator developed in the University of Edinburgh. The C-GEN is prior to conventional PM generators by absence of magnetic attraction forces between rotor and stator, absence of cogging torque, ease of manufacturing, modularity and high fault-toleration 1. Firstly, the integrated analytical design tool that couples electromagnetic, structural and thermal aspects of the generator has been introduced. Then, an optimization tool based on genetic algorithm has been used to maximize the annual electricity generation and to minimize the initial cost of the generator. The optimized generator is validated using FEA tools and the specifications of the generator has been presented.

- WS5.26 SHEK, J.K., MACPHERSON, D.E. & MUELLER, M.A.: “Minimising Capacitor Lifetime Failures in Power Converters for Wave Energy Applications”, *IEEE EMDC Conference*, Niagara, May 2011 <http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05994925>

The offshore location of wave energy converters demands a highly reliable and fault-tolerant system. Capacitors account for the majority of failures in power converters and should be replaced prior to failure to reduce system downtime. This paper presents a control methodology to reduce the rate of capacitor degradation as a means to improve fault tolerance. Modelling, simulation, and power converter control are systematically investigated using MATLAB/Simulink.

- WS5.27 CHONG, Y., MAGAHY, D., CHICK, J., MUELLER, M., McDONALD, A.S., & STATON, D.: “Numerical Modelling of an Axial Flux Permanent Magnet Machine for Convection Heat Transfer”, *1<sup>st</sup> IET Renewable Power Generation Conference*, Edinburgh, September 2011. <http://conferences.theiet.org/rpg/>

This paper presents the thermal performance of NGenTec Axial Flux Permanent Magnet (AFPM) prototype generator operating at 100rpm through the thermal analysis on single stage. The CFD model coupled the heat transfer and fluid flow modelling provides good interpretation of the thermal behaviour of the test generator at steady state. In the comparison of two ventilation conditions, the CFD simulations show the temperature drop of 4-5°C same as what the experimental measurements obtained.

- WS5.28 KEYSAN, O. & MUELLER, M.: “Superconducting Generators for Large Offshore Wind Turbines”, *1<sup>st</sup> IET Renewable Power Generation Conference*, , Edinburgh, September 2011. <http://conferences.theiet.org/rpg/>

There is a trend toward higher power rated machines for offshore wind turbines. The maximum power rating for a high-speed, geared power-takeoff system is around 5MW. For even higher power rated turbines, direct-drive generators becomes enormously heavy. Direct-drive superconducting generators have the potential to reduce the overall mass and installation costs of an offshore wind turbine. In this study, a conventional homopolar superconducting generator design is presented that is suitable for low-speed, high-torque directdrive applications. The generator has been designed with a stationary dc-field winding to increase the reliability of the generator. Also, a linear version of the generator is presented.

- WS5.29 CROZIER, R., BAILEY, H., MUELLER, M., MCKEEVER, P. & SPOONER, E.: “Analysis, Design and Testing of a Novel Direct-Drive Wave Energy Converter System”, *1<sup>st</sup> IET Renewable Power Generation Conference*, Edinburgh, September 2011. <http://conferences.theiet.org/rpg/>

A coupled electromechanical and hydrodynamic simulation of a direct-drive generator connected to a heaving buoy for wave energy conversion has been developed. The system is based around a novel linear generator referred to as ‘Snapper’ which incorporates a magnetic coupling, resulting in a latching power take-off mechanism. The system has been simulated in the time domain using the Matlab differential equation solvers, and a prototype generator designed, built and tested.

- WS5.30 CROZIER, R., BAILEY, H., MUELLER, M., MCKEEVER, P. & SPOONER, E.: “Hydrodynamic and Electromechanical Simulation of a wave Energy converter with a novel Non-Linear PTO”, *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK, September 2011. <http://www.ewtec.org/>

A coupled electromechanical and hydrodynamic time domain simulation of a direct-drive generator connected to a heaving buoy for wave energy conversion is presented. The system is based around a novel power take-off unit referred to as Snapper. The simulation is based primarily in MATLAB using its built-in Ordinary Differential Equation (ODE) solvers. These solvers act on the data derived from electromagnetic finite element analysis and from the WAMIT wave interaction simulation software. Test results of a generator prototype for comparison with the electromechanical simulation are also presented.



- WS5.31 SHEK, J.K.H., DORRELL, D.G., HSIEH, M., MACPHERSON, D.E. & MUELLER, M.A.: “Reducing bearing wear in induction generators for wave and tidal current energy devices”, *1<sup>st</sup> IET Renewable Power Generation Conference*, Edinburgh, September 2011.  
<http://conferences.theiet.org/rpg/>

Marine energy devices such as wave energy converters and tidal current turbines are set to play a significant role in contributing to electricity generating by renewable means. The offshore location where these devices operate demands high reliability and robust fault tolerance. Bearing failure is a key issue for renewable energy devices and is a cause of significant downtime in wind turbines. Bearing wear is accelerated due to unbalanced magnetic pull in the rotor of an electrical generator. This paper presents a review and assessment of methods to reduce bearing wear through both machine design and active control through power electronics.

- WS5.32 HODGINS, N., KEYSAN, O., MCDONALD, A. & MUELLER, M: “Design and Testing of a Linear Generator for Wave Energy Applications”, *Industrial Electronics, IEEE Transactions on*, vol.PP, no.99, pp.1, 0 DOI:10.1109/TIE.2011.2141103.  
<http://ieeexplore.ieee.org/search/srchabstract.jsp?tp=&arnumber=5746524&tag=1>

A linear generator topology is proposed for wave energy applications. The main significance of the generator topology is that the relative position of the magnets, copper and steel has been chosen so that there are no magnetic attraction forces between the stator and permanent magnet translator. The lack of magnetic forces and the modular nature of the generator topology makes the manufacture and assembly of the generator easier than a conventional iron-cored permanent magnet linear generator. Analytical modelling techniques are described with a genetic algorithm optimization method. The proposed topology is implemented to Archimedes Wave Swing wave energy converter. A 50 kW prototype has been built to prove the concept and the no-load and load test results are presented.

#### ***Accepted and/or In Press***

- WS5.33 HODGINS, N., KEYSAN, O., MCDONALD, A.S. & MUELLER, M.A: “Designing the C-GEN Lightweight Direct Drive Generator for Wave and Tidal Energy” *IET Renewable Power Generation Special Edition on Marine Renewables*, invited paper accepted for publication April 2011. <http://digital-library.theiet.org/IET-RPG>

The C-GEN is a novel permanent magnet generator aimed at reducing overall system mass in direct drive power takeoff applications. The design of a C-GEN generator requires the combination of electromagnetic, structural and thermal models. Models used in the development of design tools for both rotary and linear C-GEN generators are described in this paper. Then the analytical model is verified with the experiment results obtained from a 15 kW prototype. A genetic optimization algorithm is developed combining the analytical model with economical issues to search for most suitable designs for specific applications. Designs are presented using the design tool for two marine renewable applications: a wave device called Oyster developed by Aquamarine Power, and a tidal current device developed by Scotrenewables.

- WS5.34 KEYSAN, O. & MUELLER, M.: “A Homopolar HTSG Topology for Large Direct Drive Wind Turbines”, *Applied Superconductivity, IEEE Transactions on*, vol.21, no.5, pp.3523-3531, Oct. 2011. DOI: 10.1109/TASC.2011.2159005  
[http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5948361](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5948361)

For offshore wind energy, there is a trend toward larger wind turbines. The increased mass of a power-takeoff system increases the installation cost of the turbine. Direct-drive superconducting generators have the potential to reduce the installation cost of wind turbines. For a successful entry to the offshore-wind-energy market, a high-temperature superconducting generator should be as reliable as conventional generators. It is proposed that a stationary superconducting direct-current-field winding may increase the reliability of the generator. An axial-flux homopolar generator topology is proposed to be used in low-speed high-torque applications. The topology is modified by using two superconducting field windings to obtain a bipolar flux-density distribution for higher power density. Different core types and dimensions

were examined to find the most suitable design, and a conceptual design of a 6-MW 12-r/min generator is presented.

- WS5.35 DORRELL, D.G., SHEK, J.K.H., HSIEH, M. & MUELLER, M.A.: “Unbalanced Magnetic Pull in Cage Induction Machines for Fixed-Speed Renewable Energy Generators”, *Magnetics, IEEE Transactions on*, vol.47, no.10, pp.4096-4099, Oct. 2011. DOI: 10.1109/TMAG.2011.2153185 [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=6027659&tag=1](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6027659&tag=1)

The paper addresses unbalanced magnet pull (UMP) due to rotor eccentricity in cage induction generators used in wind turbines. The rationale for the work is to investigate ways to reduce bearing wear. The paper studies both static and dynamic rotor eccentricity with axial uniformity and also non-uniformity (e.g., due to a misplaced bearing). The damping action of the cage is discussed and a suitable analytical model used to calculate the UMP. Both sub- and super-synchronous UMP is investigated. It is found that the characteristic for the UMP varies depending on whether there is static or dynamic eccentricity. A use of additional damper windings is also investigated and it is found that these can help substantially reduce the UMP when the machine is lightly-loaded with dynamic eccentricity. A previously investigated 10-pole machine is used in the simulations. The analytical model has previously been validated for this. The range of simulation covers both motoring and generating modes ( $\pm 10\%$  slip). This, together with the simulation of the UMP damping windings, represent a good contribution to the literature since they have not been previously addressed.

#### WORKSTREAM 6 - Moorings and positioning

- WS6.1 JOHANNING, L., SMITH, G. H. & BULLEN, C.: “Large scale mooring line experiments and comparison with a fully dynamic simulation program with importance to WEC installation”, *17th Int. Offshore (Ocean) and Polar Engineering Conference, ISOPE 2007, 01*. July 1-6, 2007, Lisbon, Portugal. <http://www.isopec.org/publications/proceedings/ISOPE/ISOPE%202007/papers/107JSC-214joha.pdf>

Large scale experiments with an 82t vessel moored on a 22mm single chain at a mean water depth of 24m were performed at Scapa Flow (Orkney) to study mooring conditions for the installation of wave energy converters (WECs). Tension and response behaviour were found for various pre-tension conditions using horizontal and axial load measurement techniques and a GPS system for tracking the motion of the vessel. The pre-tension conditions were chosen to provide a slack, fully lifted and taut mooring line arrangement. The study also includes a numerical model of the experiments by applying line properties, installation conditions and the displacement measurements to the simulation and calculating the resulting tensions. The experimental problems that were overcome to obtain meaningful results from large scale experiments under real sea conditions are explained and the importance of mooring line dynamics for WECs is discussed.

- WS6.2 JOHANNING, L., SMITH, G. H. & WOLFRAM, J.: “Measurements of static and dynamic mooring line damping and their importance for floating WEC devices”, *Ocean Engineering* 34 (2007) p.1918–1934 <http://www.sciencedirect.com/science/article/pii/S0029801807001126>

The dynamic response of the mooring line will be a dominant factor to consider in their use for the station keeping of a wave energy converter (WEC). Due to the relatively small size of WECs and their being moored in relatively shallow waters the effect of waves, tide and current can be of greater significance than for other floating offshore systems. Axial line stretching and high-frequency ‘top-end’ dynamics can importantly modify damping and top-end loading. If a ‘farm’ of devices is to be considered then limitations in sea space may necessitate that the devices be relatively densely packed. This will mean that the ‘footprint’ of the mooring should be constrained, to ensure that the moorings from each device do not interfere and this will have great significance for the loading experienced by the line. One must also consider how the mooring system might change the response of the WEC and so alter its ability to extract power from the waves. Unlike a typical offshore system, the design of moorings for a WEC device must consider reliability and survivability, and the need to ensure efficient energy conversion. The design and operation of a chain mooring for a WEC is considered here. Generic experimental measurements of mooring line damping were conducted in the Heriot-Watt University wave basin at a scale of 1:10. The

measurements were conducted on a single mooring line for surge motions and include the study of axial stretching and high top-end dynamics. The laboratory procedures were designed to resemble tests undertaken earlier at 'full' scale in 24m water depth. The measurements were also compared with numerical studies. The experimental findings for WEC devices, supports the conclusion that dynamic mooring line motion will be an important variable, needing to be considered carefully within the design.

- WS6.3 JOHANNING, L. & SMITH, G. H.: "Station keeping study for WEC devices including compliant chain, compliant hybrid and taut arrangements", *Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering (OMAE2008)*, June 15-20, 2008, Estoril, Portugal.  
<http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=ASMECP00200804823400058700001&idtype=cvips&gifs=yes>

This paper presents results from the third phase of large scale mooring investigation at the Scapa Flow in Orkney, Scotland, for wave energy applications. It considers the suitability of three slack mooring line configurations, namely, i) compliant chain, ii) complaint hybrid and iii) taut fibre rope arrangement. This investigation is extended with a numerical study analysing the station keeping criteria for the three slack line configurations and that of a taut system for wave energy converter installations. The results are used to discuss the suitability of the individual mooring line configurations and that of the taut arrangement. This paper is partially to provoke a discussion on the advantages of a taut mooring system and raise the issues that need to be solved if they are to be practicable.

- WS6.4 JOHANNING, L. & SMITH, G. H.: "Improved measurement technologies for floating wave energy converter (WEC) mooring arrangements", *Underwater Technology, vol. 27, issue 4, (2008), pp. 175-184.* <http://www.sut.org.uk/>

Large-scale experiments were conducted under real sea conditions to support the investigation of non-linear mooring line effects and their importance to moored wave energy device installations. The problems associated with such testing are described, and a discussion of solutions to overcome these is given. An improvement of the experimental apparatus and procedures resulted in meaningful data that could be compared with tank testing and numerical models. The lessons learned have provided confidence in the future implementation of an offshore mooring test facility off the Cornwall coast.

- WS6.5 MCCARTER, W. J., LINFOOT, B. T. L., CHRISP T.M.C. & STARRS, G.: "Performance of concrete under XS1, XS2 and XS3 environments", *Magazine of Concrete Research, 60, 4, May, 2008, 261-270. ISSN: 0024-9831, E-ISSN: 1751-763X*  
<http://www.icevirtuallibrary.com/content/article/10.1680/mac.2008.60.4.261>

An extensive chloride-profiling programme was undertaken over an eight-year period on nine concrete pier-stems placed at a marine location to represent XS1, XS2 and XS3 environmental exposure conditions as defined in European Standard EN 206-1. The pier-stems were 2.0 m high and octagonal in plan with each vertical face 0.66 m wide and were constructed in groups of three (one each placed at the locations defined above): one group, which was used as a benchmark, represented plain Portland cement concrete; the second group had a waterproofing agent (Caltite) added at the time of mixing; and the third was treated with silane. Chloride concentration profiles were taken at a number of locations on each pier-stem, which were subsequently used to evaluate the temporal change in effective diffusion coefficient and surface chloride concentration for the different exposure conditions. In addition, it allowed assessment of the relative performance of the plain concrete, Caltite concrete and silaned concrete pier-stems with regard to chloride ingress.

- WS6.6 ASHTON, I., JOHANNING, L. & LINFOOT, B.: "Measurement of the effect of power absorption in the lee of a wave energy converter", *28th ASME International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2009)*, Honolulu, Hawaii, 31 May - 5 June 2009.  
<http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=ASMECP00200904344400102100001&idtype=cvips&gifs=yes>

Monitoring the effect of floating wave energy converter (WEC) devices on the surrounding wave field will be an important tool for monitoring impacts on the local wave climate and coastlines. Measurement

will be hampered by the natural variability of ocean waves and the complex response of WEC devices, causing temporal and spatial variability in the effects. Measurements taken during wave tank tests at MARINTEK are used to analyse the effectiveness of point wave measurements at resolving the influence of an array of WEC on the local wave conditions. The variability of waves is measured in front and in the lee of a device, using spectral analysis to identify changes to the incident wave field due to the operating WEC. The power capture and radiation damping are analysed in order to predict the measured changes. Differences in the wave field across the device are clearly observable in the frequency domain. However, they do not unanimously show a reduction in wave energy in the lee of a device and are not well predicted by measured power capture.

WS6.7 VICKERS, A. W. & JOHANNING, L.: “Comparison of damping properties for three different mooring arrangements”, *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. <http://www.ewtec2009.se/>

For the safe operation of floating wave energy converters (WEC's) it is required to obtain deeper understanding of the moored device as a coupled system. The motion of a WEC is dependent on the stiffness, mass and the damping characteristics of the body and the mooring system, as well as influenced by the power take of system. In order to understand the effect of the individual contributions to the coupled system, the influence of the individual parameters needs to be understood. Typical offshore oil and gas installations, in moderate water depths, are often moored using catenary configurations within linear load-extension characteristics. In many applications the damping contribution due to the mooring system is within a linear regime and hence can be applied in a linear fashion.

Due to their physical size and the wish to install the WEC in an energetic environment, there is an increased risk that the moor will be operating in a load-extension range with non-linear characteristics. Furthermore, it is likely that for the station keeping of WECs compliant configurations are used with fibre rope sections. These would have an effect on the stiffness and damping characteristic of the mooring system [1, 2], which could importantly affect the coupled motion of a moored WEC device. The affect towards the power conversion and/or ultimate peak loads needs to be understood to allow for a safe station keeping that does not adversely affect the energy conversion.

A detailed investigation of mooring line stiffness and damping properties has been conducted at large scale tests in the Scapa Flow at Orkney. Three different mooring arrangements namely, catenary chain, hybrid chain-rope and nylon rope S-shape were investigated. Preliminary analysis was presented to identify the stiffness characteristics for these large scale tests [3]. Within the analysis presented here the main focus will be given to the energy dissipation (damping), comparing the different arrangements using the 'indicator-diagram method'. The intention of this study is to identify the damping properties of the individual mooring arrangements in order to provide information towards the analysis of a coupled system.

The damping dependency is discussed in respect to i) the configuration, ii) pre-tension, iii) surge amplitude and iv) forced frequency oscillation. It is recommended to use a non-dimensional damping parameter ( $E/T0h$ ), where the energy dissipation is scaled with respect to the pre-tension and water depth, instead of the traditionally parameter ( $E/awh$ ). A linear trend was observed for all configurations once the parameter ( $E/T0h$ ) was plotted against the surge amplitude ratio ( $a/h$ ).

WS6.8 BRYDEN, I. & LINFOOT, B. T.: “Wave and current testing of an array of wave energy converters”, *Proc. of the Hydralab III Joint User Meeting*, Hannover, Germany, January 2010. [http://www.hydralab.eu/hydralabIII/proceedings/NTNU-18\\_Bryden.pdf](http://www.hydralab.eu/hydralabIII/proceedings/NTNU-18_Bryden.pdf)

This paper briefly describes the physical model testing of an array of generic wave energy devices undertaken in the NTNU Trondheim basin during 8th to 20th October 2008 funded under the EU Hydralabs III initiative. The aim of the tests was to provide data for the validation of numerical models of the device motions, power recovery and mooring components when moored in a closely spaced array. The tests were not intended to be proof-of-concept tests for a particular device and none of the tests were designed to study survival response under extreme loading. Tests were completed at 1/20 scale on a single oscillating water column device and on close-packed arrays of three and five devices following

calibration of instrumentation and the wave and current test environment. The arrays were tested under similar environmental loading with partial monitoring of mooring forces and motions. A total of ninety-five tests were undertaken including wave and current calibrations and damping tests. Analysis of the data indicates that close-packed arrays of energy converters may be more efficient in energy capture than the same number of similar devices. No significant current induced-motions on the WECs were observed in any array configuration.

WS6.9 KRIVSTOV, V. & LINFOOT, B. T.: “Physical model investigation of mooring loads in arrays of wave energy converters”, *Proc. 1st European Congress of the IAHR*, Edinburgh, Scotland, UK, May 2010.

<http://www.iahreurope.info/edinburgh2010/home/index.asp>

This paper describes the physical model testing of an array of wave energy devices undertaken in the NTNU Trondheim basin during 8th to 20th October 2008 funded under the EU Hydralabs III initiative, and provides a preliminary analysis of the extreme mooring loads. Tests were completed at 1/20 scale on a single oscillating water column device and on close-packed arrays of three and five devices following calibration of instrumentation and the wave and current test environment. One WEC was fully instrumented with mooring line load cells, optical motion tracker and accelerometers and tested in regular waves, short-and long-crested irregular waves and current. The wave and current test regimes were measured by six wave probes and a current meter. Arrays of three and five similar WECs, with identical mooring systems, were tested under similar environmental loading with partial monitoring of mooring forces and motions.

Preliminary analysis of the data indicate that close –packed arrays of energy converters may be more efficient in energy capture than the same number of similar devices. The majority of loads on the mooring lines appeared to be broadly consistent with both logistic and normal distribution, whilst the right tail appeared to confirm to the extreme value distribution. Comparison of the loads at different configurations of WEC arrays suggests that the results are broadly consistent with the hypothesis that the mooring loads should differ. In particular, the results from the tests in short crested seas conditions give an indication that peak loads in a multi WEC array may be considerably higher than in 1-WEC configuration.

The test campaign has contributed essential data to the development of Simulink and Orcaflex models of devices which include mooring system interactions and data has also been obtained for inter-tank comparisons, studies of scale effects and validation of mooring system numerical models. Testing of arrays of WEC in Strangford Lough, Northern Ireland is planned to begin in Summer 2010.

WS6.10 KRIVSTOV, V. & LINFOOT, B.T: “Modelling of disruption to benthic habitats and overall ecosystem functioning by marine renewable energy installations”, *ECEM 2011, F. Jordán, M. Scotti, and M. Lencioni, Editors. 2011, Temi Press: Riva del Garda, Italy. p. 117 - 118.*

<http://www.private-eye.it/ecem2011/>

This paper presents the research carried out in the marine renewables group of Heriot-Watt University, where the physical models of wave energy converters are first tested in the wave basin, and the results of their behaviour are then compared to the simulations performed using mathematical modelling. An OrcaFlex model is used to assess the scouring effect on bottom sediments and consequent disruption of benthic habitats, and open water tests are being conducted to compare the model performance with the actual observation. The output from OrcaFlex is then imported to Matlab, where the affected area is calculated using the time series of coordinates of touch down points of mooring lines. The results show that the area of benthic habitats adversely affected by the leading mooring line on a typical wave energy converter monotonically increases with the increase in wave height. In regular waves of 6 m height and 8 s period, the area of benthic habitats adversely affected by the mooring lines may exceed 60 m<sup>2</sup>. In irregular waves, increases to H<sub>s</sub> from 4 to 6 and 8 m, resulted in the increase of the benthic habitats disrupted by a mooring line of, respectively, 37% and 44%. In addition to the direct effect on benthic habitats, sediment erosion by mooring lines will effect a whole range of ecosystem processes, e.g. due to changes in biogeochemical cycling and light penetration. These issues should be given a due consideration in calculations of ecological risks and EIA of any moored objects.

WS6.11 KRIVSTOV, V. & LINFOOT, B.T., & HARRIS, R.E.: “Investigation of the effects of mooring line surface buoys on the extreme mooring loads of wave energy converters”, in *ENSUS. 2011 Newcastle*. <http://conferences.ncl.ac.uk/ensus/authors.html>

This presentation will describe the physical model testing of a wave energy device undertaken in the Heriot-Watt wave basin as part of the SuperGen2 project, and will provide an analysis of extreme mooring loads. Tests were completed at 1/20 scale on a single oscillating water column device deployed with a 3-line mooring configuration. The WEC was fully instrumented with mooring line load cells and an optical motion tracker. The tests were preceded by calibration of instrumentation and the wave test environment, and carried out in long crested waves regimes with 12 combinations of peak period and significant wave height (Hs: 2, 3 & 4 m; Tp: 12, 10 & 8 s). The main objective for these experiments was to examine the effect of shape and size of the surface buoy on the leading mooring line on the maximum loads and the excursion of the device. In total, three series of tests were performed for three different buoys. Buoys 1 and 2 were both of spherical shape, with Buoy 2 being considerably larger. Buoy 3 was of a ‘light bulb’ shape, with the volume similar to Buoy 2.

The results show that the wave motion induces a complex motion dynamics of the device, consisting of both wave frequency and low frequency components approximating to the natural frequency of mooring system. This interplay is particularly apparent in the surge motion, and in the loads in the leading mooring lines. Comparison of the loads at different configurations of the tethered buoy suggests that the results are consistent with the hypothesis that the mooring loads should differ. In particular, the results give an indication that when the spectral peak Tp is close to the natural period of the moored device (i.e. peak period 8 and 10 s), peak loads in a configuration with a smaller buoy (i.e. buoy1) may be considerably higher than for a larger buoy configuration (e.g. buoys 3 and 2).

The magnitude of the extreme loads was remarkably higher in those conditions when the peak period was close to 8 s, which is the natural period of the moored device. Based on the results presented here, for Tp=10 and 8 s, out of the configurations tested those with the buoys 2 and 3 were clearly better (i.e. in terms of alleviation of extreme mooring loads) than the configuration with buoy 1. It should be noted, however, that at the Tp=12 the best performer was buoy 1. In particular, the maximum loads for the lower mooring line did not differ significantly in relation to the Hs at this configuration. Hence the best configuration may depend upon the expected environmental conditions.

#### **WORKSTREAM 7 - Advanced control and network integration**

WS7.1 HARRISON, G.P., PICOLLO, A., SIANO, P. & WALLACE, A. R.: “Hybrid GA and OPF evaluation of network capacity for distributed generation connections”, *Electric Power Systems Research, Volume 78, Issue 3, March 2008, Pages 392-398, ISSN 0378-7796, DOI: 10.1016/j.epsr.2007.03.008*. <http://www.sciencedirect.com/science/article/pii/S0378779607000636>

Many methods have been applied to examine the capacity of existing distribution networks to accept distributed generation (DG). One aspect missing from existing approaches is the capability to efficiently site and size a predefined number of DGs. Here, a hybrid method employing genetic algorithms and optimal power flow aims to overcome this shortcoming. It could be applied by distribution network operators to search a network for the best sites and capacities available to strategically connect a defined number of DGs among a large number of potential combinations. Some applications of the proposed methodology in the UK under current Ofgem financial incentives for DNOs confirmed its effectiveness in siting and sizing an assigned number of DG units.

WS7.2 PRICE, A. A. E., FOREHAND, D. I. M., & WALLACE, A. R.: “Time-span of future information necessary for theoretical acausal optimal control of wave energy converters” *10th European Control Conference (ECC'09)*, Budapest, Hungary, 23-26 August 2009. – **Invited paper** <http://www.conferences.hu/ecc09/>

Optimal control of a wave energy converter (WEC) in polychromatic seas is possible only with accurate future knowledge of wave elevation, excitation force or WEC state. The required future knowledge is related to the bandwidth of the wave spectrum. A new concept called premonition time is introduced,

which is defined as the time by which the time-span of the required future knowledge exceeds that of the available future knowledge. The effect of the size of a WEC on the premonition time, and suitable methods for prediction of future state, are also discussed.

WS7.3 PRICE, A. A. E., DENT, C.J. & WALLACE, A. R.: “Frequency domain techniques for numerical and experimental modelling of wave energy converters”. *Proc 8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 2009 [www.ewtec2009.se/](http://www.ewtec2009.se/)

This paper discusses the restrictions on frequency domain modelling of wave energy converters (WECs). It is shown that, for a model where the radiation is represented as causal, and where the control signal is not acausal, a frequency domain model is suitable for finding the post-transient, linear, causal response of a WEC. The common use of models that do not represent the casual nature of radiation (memory), or that include an acausal control signal, are identified in the literature. Arguments are presented for restricting both models to sinusoidal motion. Correct and incorrect applications of these restricted models to numerical and experimental work are discussed, with examples given from literature. Several papers are identified that could be interpreted as stating that frequency domain modelling of WECs is restricted to sinusoidal motion only. However, it is shown that these papers are in fact discussing the limitations of models where the control signal, or the WEC itself, are represented as mass-spring-damper systems.

WS7.4 KIPRAKIS, A. E., NAMBIAR, A. J., FOREHAND, D.I.M & WALLACE, A. R.: “Modelling arrays of wave energy converters connected to weak rural electricity networks”, *1<sup>st</sup> International SuperGen Conference, Nanjing, China, April 2009*.  
<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5348024>

This paper describes a modelling framework developed in Matlab/Simulink that has been used to study, analyse and improve the network integration of wave energy converters (WECs). It presents and discusses a generic, time domain, resource-to-wire model that can be used to explore the effects of: increased device numbers, array size and physical positioning; and the adjustment of control parameters. The three-dimensional wave field is modelled as non-stationary, with statistical characteristics that are extracted from measured wave elevation time series to simulate increasingly realistic sea conditions. Each heaving buoy has high-pressure oil power take off with on-board energy storage, driving doubly fed induction generators (DFIGs). The results obtained from simulations using this model are used to demonstrate the overall effects of storage on real power production, and the effects of imaginary power control on network voltage profile. The opportunities for improved network integration are identified and discussed.

WS7.5 TAYLOR, C.J., STABLES M.A., CROSS, P., GUNN, K. & AGGIDIS G.A.: “Linear and non-linear control of a power take-off simulation for wave energy conversion”, *Proc 8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 2009 [www.ewtec2009.se/](http://www.ewtec2009.se/)

This article focuses on control of the power take off (PTO) element of a point absorber wave energy converter. The research is based on a nonlinear simulation of a PTO hydraulic circuit, in which the piston velocity and generator torque act as ‘disturbance’ and control actuator variables respectively, whilst the damping force is the controlled output variable. The piston velocity is generated by a hydrodynamic simulation model that reacts to both the damping force and sea wave profile. The damping force set point will be obtained from an associated power capture optimisation module and may be time varying. However, it is clear that such an adaptive tuning system also requires high performance ‘low-level’ control of the device actuators, in order to fully realise the benefits of optimisation. In this regard, the present article illustrates use of the Proportional-Integral-Plus (PIP) control methodology as applied to the PTO simulation. In their simplest linear form, such PIP controllers do not account for the interconnected system variables mentioned above. For this reason, the research also considers ‘feed-forward’ and ‘state-dependent’ forms of PIP control, in which the piston velocity is appended to a non-minimal state space representation of the system.

WS7.6 CROSS, P., TAYLOR, C.J. AND AGGIDIS G.A.: “Feed-forward control of a power take-off simulation for wave energy conversion”, *20th International Conference on Systems Engineering Coventry*, UK, 2009  
<http://www.coventry.ac.uk/researchnet/ctac/meetingsandconferences/icse2009/Pages/ICSE2009.aspx>

This article is concerned with the control of a non-linear model of a hydraulic power take-off (PTO) device for a wave energy converter. In this simulation, the torque applied to the shaft of a hydraulic motor by an electrical generator acts as the control actuator variable, the damping force in the PTO as the controlled output variable and the hydraulic piston driving the PTO considered disturbance acting upon the system.

Other research at Lancaster University is concerned with the optimisation of such devices for non-linear waves. Fast and accurate feedback control of actuators in the PTO is necessary to realise fully the benefits of this optimisation. In the work described here, a proportional-integral-plus (PIP) control methodology is applied to the PTO simulation. In their simplest, linear form, PIP controllers do not account for interconnected system variables, such as those described by this model. For this reason, several forms of multiple-input, 'feed-forward' PIP control have been investigated.

WS7.7 PRICE, A. A. E., DENT, C. J. & WALLACE, A. R.: "On the capture width of wave energy converters", *Applied Ocean Research*, Volume 31, Issue 4, October 2009, Pages 251-259, ISSN 0141-1187, DOI: 10.1016/j.apor.2010.04.001.  
<http://www.sciencedirect.com/science/article/pii/S0141118710000234>

This paper extends the theory on capture width, a commonly used performance indicator for a wave energy converter (WEC). The capture width of a linear WEC is shown to depend on two properties: the spectral power fraction (a property introduced in this paper), which depends entirely on the sea state, and the monochromatic capture width, which is determined by the geometry of the WEC and the chosen power take off (PTO) coefficients. Each of these properties is examined in detail. Capture width is shown to be a measure of how well these two properties coincide. A study of the effects of PTO control on the capture width suggests that geometry control, a form of control that has not been the focus of much academic research, despite its use in the wave energy industry, deserves more attention. The distinction between geometry control and PTO control is outlined. While capture width is a valuable design tool, its limitations must be recognised. The assumptions made in the formulation of capture width are listed, and its limitations as a tool for estimating annual power capture of a WEC are discussed.

WS7.8 BOEHME, T., HARRISON, G.P. & WALLACE, A. R.: "Assessment of Distribution Network Limits for Non-firm Connection of Renewable Generation", *IET Renewable Power Generation*, Vol 4, Issue 1, 64-74, March 2010 <http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05383263>

Before new renewable generators can be connected to the electricity network, it is necessary to carefully evaluate the impact they will have. Firm connection agreements are based on snapshot assessments of the worst-case situation of maximum generation and minimum demand, which restrict renewable capacities despite infrequent occurrence. This work describes how time series of several renewable generation technologies together with demand can be applied to examine the opportunities and challenges offered by non-firm generation connections. It applies optimal power flow to extract maximum energy from available renewable resources while using curtailment of generation to maintain the network within thermal and voltage limits. By way of a case study of potential wind, wave and tidal current development in the Orkney Islands, Scotland, the analysis provides estimates for the degree of curtailment and consequent economic impact a renewable generator operating under non-firm connection may experience. The methods described provide a first-level analysis that could facilitate appraisal of non-firm connections at the planning stage by estimating the consequences of concurrent generation and demand as well as the frequency and duration of necessary curtailments.

WS7.9 CROSS, P., TAYLOR, C. J. & AGGIDIS, G. A.: "Continuous-time feed-forward proportional-integral-plus control" *UKACC International Conference (CONTROL 2010)*, 7th – 10th September, Coventry, UK. <http://vs-ec-ctacconf.coventry.ac.uk/drupal-6.14/>

Most of the research into Non-Minimal State Space (NMSS), Proportional-Integral-Plus (PIP) control system design has been in the discrete-time domain. However, continuous-time models can have a number of advantages, particularly for fast sampled systems or when it is essential that the control system responds quickly to an unexpected disturbance. The present article applies continuous-time NMSS/PIP



design to two practical examples, namely a connected pair of DC electric motors in the laboratory, and a nonlinear simulation of a hydraulic power-take-off element for a wave energy converter. Both applications include measured disturbance inputs. Therefore, the article also develops and evaluates feedforward control structures, including one based on an extended continuous-time NMSS model.

WS7.10 MCCABE, A. P., STABLES, M. A. & AGGIDIS, G. A.: “A frequency-response design method for the control of wave energy converters in irregular seas”, *3rd International Conference on Ocean Energy – ICOE 2010*, 6th – 8th October 2010, Bilbao, Spain.  
<http://www.icoe2010bilbao.com/ing/index.aspx>

In this paper we present a method of controlling wave energy converters (WECs) in irregular seas. The method controls the WEC so that its displacement frequency response achieves a predetermined characteristics, which is chosen to enhance performance. The design of the controller described is based upon a feedback structure, through deriving the control force from the required displacement of the WEC, rather than the actual displacement. The control setpoint (the required displacement) is synthesized from the incident wave, so prediction of the incoming waves is required, in common with other methods of control in irregular seas. The method is demonstrated using a linear time-domain model of a heaving cylinder. The control signal is generated using both impulse-response functions and transfer functions in order to compare the performance of each, in terms of control signal accuracy and power output, under conditions of reduced wave prediction time. The characteristics of the control force demand and power flow in the controlled system, and the effect on performance of errors both in synthesizing and predicting the incoming wave are investigated. The application of the controller design to a model incorporating non-linearity is also considered.

WS7.11 NAMBIAR, A. J., KIPRAKIS, A. E. & WALLACE, A. R.: “Voltage quality control of a 1MW wave farm connected to weak, rural electricity networks”, *45th International Universities' Power Engineering Conference - UPEC 2010*, 31st August - 3rd September 2010, Cardiff, UK.  
<http://www.upec2010.com/>

This paper describes a wave-to-wire model of an array of wave energy converters (WECs) developed in MATLAB/Simulink. The model has been used to study the effects of connecting a 1MW wave farm to a weak, rural electricity network. Voltage quality issues are examined and methods by which these impacts can be mitigated are discussed. The operation of the wave farm using four different controllers used for improving the voltage quality is compared. The control methods tested are: constant voltage operation, constant power factor operation, On Load Tap Changing Transformer (OLTC) operation, automatic voltage and power factor controller (AVPFC) operation and fuzzy logic power factor controller operation. The applicability of these control methods for three different sea states – highly, moderately and weakly energetic, is analysed. The pros and cons of using these methods are examined. Prospects for further work are identified and discussed.

WS7.12 NAMBIAR, A. J., KIPRAKIS, A. E. & WALLACE, A. R.: “Quantification of voltage fluctuations caused by a wave farm connected to weak, rural electricity networks”, *14th International Conference on Harmonics and Quality of Power - ICHQP 2010*, 26th – 29th September 2010, Bergamo, Italy. <http://emma.polimi.it/emma/showEvent.do?idEvent=32>

This paper describes a wave-to-wire model of an array of wave energy converters developed in MATLAB/Simulink. The effects of connecting a 1 MW wave farm to a weak, rural electricity network are investigated. Impacts of the wave farm on voltage quality are examined and both conventional and more intelligent control methods by which these impacts can be mitigated are discussed. The control methods compared are: constant voltage operation, constant power factor operation, On Load Tap Changing Transformer (OLTC) operation, automatic voltage and power factor controller (AVPFC) operation and fuzzy logic power factor controller operation. The applicability of these control methods are compared using certain indices - flicker severity index, voltage fluctuation index and global voltage regulation. Drawbacks of power factor control, voltage control and control using the OLTC transformer and the advantages of using more intelligent control methods, like the AVPFC or the fuzzy logic power factor controller, are established.

- WS7.13 NAMBIAR, A. J., KIPRAKIS, A. E., FOREHAND, D. I. M. & WALLACE, A. R.: “Effect of array configuration, network impacts and mitigation of arrays of wave energy converters connected to weak, rural electricity networks”, *3rd International Conference on Ocean Energy – ICOE 2010*, 6th – 8th October 2010, Bilbao, Spain. <http://www.icoe2010bilbao.com/ing/index.aspx>

This paper describes a wave-to-wire model of an array of wave energy converters (WECs). Effects of the physical positioning of the WECs and the adjustment of control parameters are presented. The results obtained from this paper demonstrate the overall effects of storage on real power production and imaginary power control on network voltage profile. Characteristics of the raw mechanical power produced by an array of 48 WECs are also presented. The opportunities for improved network integration are identified and discussed.

- WS7.14 CROSS, P., STABLES M.A., TAYLOR, C.J. AND AGGIDIS G.A.: ‘State dependent feed–forward control of a wave energy converter model’ *Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC)*, 5-9 September; Southampton, UK. 2011 [www.ewtec.org/](http://www.ewtec.org/)

This paper considers the control of a hydraulic power take–off (PTO) simulation, forming part of a wave energy converter model. The resonant frequency of the device is tuned to the dominant frequency of the incoming wave spectrum by adjusting the PTO damping force, considered the controlled variable. The torque supplied by a generator acts as the control input, with the piston driving the PTO representing a disturbance.

Adaptive tuning strategies require high performance actuator control to realise the benefits of optimisation; the work presented here utilises proportional–integral–plus (PIP) control. In their simplest form, PIP controllers cannot account for the interconnected system variables present in the PTO simulation, resulting in relatively poor performance. Therefore, previous research has considered several ‘feed–forward’ forms of PIP control, in which disturbance is utilised as a measured variable.

Although feed–forward controllers offer improved disturbance rejection over standard PIP controllers, when the disturbance signal is sufficiently far from the operating level upon which the controller is based, the response to disturbances deteriorates. For this reason, the present article develops a non–linear feed–forward filter, the gains of which are updated at each sample, resulting in almost complete disturbance rejection.

## WORKSTREAM 8 - Reliability

- WS8.1 THIES, P. R., FLINN, J. & SMITH, G. H.: “Is it a showstopper? Reliability assessment and criticality analysis for wave energy converters”, *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 7-10 September 2009. [www.ewtec2009.se/](http://www.ewtec2009.se/)

The reliability of wave energy converters (WECs) is a key issue that has to be addressed in order to make them a viable energy option. At this stage of early industrial development the reliability assessment of WECs is a challenging task. In this paper existing reliability methods, namely Reliability Block diagrams, have been applied to a notional configuration. It was found that omnipresent lack of failure rate data makes rather crude adjustments of often generic data necessary which generally lead to rather unfavourable and highly uncertain results. Reliability data is either not available due to sparse field experience or is kept confidential, within different project developments to secure competitive advantages and intellectual property. In order to foster the progress of the marine energy industry, the reliability of devices must be demonstrated and improved. This requires a joint effort between industry stakeholders to collect, share and disseminate existing failure knowledge and future operational experience.

- WS8.2 VAL, D. V.: “Aspects of reliability assessment of tidal stream turbines”, *10th International Conference on Structural Safety and Reliability (ICOSSAR 2009)*, Osaka, Japan, 13-17 September 2009. <http://www.dist.unina.it/proc/2009/ICOSSAR10/pdf/CH473.pdf>

The paper considers general issues related to the reliability and availability assessment of tidal stream turbines. It starts with a brief description of the technology and the main types of existing (or proposed)

turbines. A generic tidal stream turbine, which is used for reliability studies, is also described. A methodology for the turbine reliability analysis is then presented. A tidal stream turbine is a complex system consisting of structural, mechanical and electronic subsystems and components, therefore, the methodology should involve methods of both structural and system reliability. Since this a new technology the main problem with the application of system reliability methods is a lack of statistical data on failures of mechanical and electronic subsystems/components of tidal stream turbines. Possible ways of dealing with this problem are discussed, in particular possibility to use relevant data collected for wind turbines. Finally, the concept of availability in relation to tidal stream turbines and factors affecting it are considered.

WS8.3 ILIEV, C. & VAL, D.: “Reliability evaluation of power train of tidal current turbines”, *Proc. of 5<sup>th</sup> International ASRANET Conference*, Edinburgh, 2010. <http://www.maritime-conferences.com/asranet2010-conference/>

Tidal current turbines are designed to extract energy from bi-directional tidal current. A power take – off train of such a turbine typically consists of a rotor, gearbox, brake, coupling, generator, converter and controllers. The rotor is attached to the main shaft, which transmits power to the generator through the gearbox. A seal (main seal) is mounted on the main shaft to prevent entry of sea water into the gearbox and to retain lubricating oil inside it. The locating bearing of the main shaft (main bearing) is positioned immediately after the main seal. The reliability assessment of tidal current turbines, being a new technology, is hampered by lack of historical data on failures. One possible approach is modification of the base failure rate to conditions of a particular application by the so-called ‘influence’ factors. In this paper modification of the base failure rate to conditions of tidal current turbines is applied to estimate failure rates of the main bearing. The bearing has to accommodate both radial and axial loads and tolerate misalignment. Those requirements are met by spherical roller thrust bearings and spherical roller bearings. Three different bearings are considered, which allows comparison of design variants. Results are compared with bearing life calculations by the so called ‘life’ factors according to ISO 281 - 1977. To account for uncertainties in bearing loads, lubricant viscosity, lubricant contamination, etc. an improved model of bearing failures has been developed. The influence factors and the failure rate are treated as a random variable and the distribution of the latter is obtained by Monte Carlo simulation. Effect of input data variation on the failure rate is presented. The failure rate distribution is approximated by a lognormal distribution and a 90% confidence interval is established.

WS8.4 ILIEV, C. & VAL, D.: “Tidal current turbine reliability: power take-off train models and evaluation”, *3rd International Conference on Ocean Energy – ICOE 2010*, 6th – 8th October 2010, Bilbao, Spain. <http://www.icoe2010bilbao.com/ing/index.aspx>

Tidal current turbines are designed to extract energy from bi-directional tidal current. Power take - off train of such a turbine typically consists of rotor, gearbox, mechanical brake, coupling, generator, converter and controllers. The rotor is attached to the main shaft, which transmits power to a generator through a gearbox. The main seal mounted on the main shaft has the dual purpose of retaining lubricant and preventing the ingress of seawater. The locating bearing of the main shaft (main bearing) is positioned immediately after the main seal. Reliability assessment of tidal turbines, being a new technology, is hampered by lack of historical data on failures. A method for estimation of failure rates by adjustment of base failure rate to conditions of tidal turbines is applied. Failure rates are assumed constant and three components are considered in details: main shaft, main seal and main bearing. An improved reliability model of the main bearing with variable failure rate is developed, which takes into account uncertainties associated with bearing load, lubricant viscosity, lubricant contamination. Failure rate distribution, obtained using Monte Carlo simulation, is approximated by a lognormal distribution and 90% confidence interval is established.

WS8.5 ILIEV, C. & VAL, D.: “Failure rates assessment for power take-off train of tidal current turbine”, *Proc. of World Renewable Energy Congress XI*, Abu Dhabi, 2010. <http://www.wrenuk.co.uk/>

Tidal current turbines are designed to convert kinetic energy of tidal current into electricity. Power take-off train typically consists of a rotor, gearbox and generator. Failure rate assessment of the power train components is carried out by adjustment of their base failure rates to conditions of tidal current turbines.

Failure rates are assumed to be constant and three components are analysed in detail: main bearing, main seal and main shaft. An improved model of the main bearing failures has been developed, which takes into account uncertainties in bearing loads, lubricant viscosity and contamination. Failure rate is treated as a random variable and its distribution, generated by Monte Carlo simulation, is approximated by a lognormal distribution. The 90% confidence interval is established. Effect of the input data variation on failure rate is examined. The methodology presented allows comparison of variants in design for reliability of turbine components.

WS8.6 JOHANNING, L., THIES, P.R. & SMITH, G.H.: “Component test facilities for marine renewable energy converters”, *Proc. Int. Conf. Marine Renewable and Offshore Wind Energy, The Royal Institution of Naval Architects (RINA), 21-23 APRIL 2010*.  
<https://eric.exeter.ac.uk/repository/handle/10036/119885>

This paper describes how the PRIMaRE group at University Exeter is engaging in the establishment of appropriate reliability methods suitable for application to marine renewable devices with a key area being the production of suitable failure rate data for the marine renewable energy industry. This activity seeks to mitigate uncertainties and cost implications associated with the reliability assessment of marine energy converters (MECs) due to an omnipresent lack of applicable failure rate data.

The capability of two facilities, namely i) the South Western Mooring Test Facility (SWMTF) and ii) the Dynamic Marine Component Test facility (DMAc), to perform specimen and accelerated component testing is discussed. A case study, using data from wave tank tests and numerical simulations performed for the SWMTF, serves to illustrate how evidence of component reliability under operational conditions could be provided.

WS8.7 THIES, P.R., JOHANNING, L., & SMITH, G.H.: “Assessing loading regimes and failure modes of marine power cables in marine energy applications”, *Proc. 19th Advances in Risk and Reliability Technology Symposium, pp. 237-251, April 12-14, 2011*.  
<http://www.lboro.ac.uk/departments/aaets/arts/papers.html>

Highly reliable marine power cables are imperative for the cost-effective operation of marine energy conversion systems. Cable manufacturers and installers have considerable experience with marine power cables when deployed to operate under static or dynamic load conditions, but highly dynamical power cables for marine renewable energy converters have large uncertainties.

The mechanical loadings of a power cable attached to a floating marine energy converter will be considerably different to the present applications like remotely operated vehicles (ROVs) or oil and gas umbilicals. The floating structure responds to the wave action and transfers this dynamic motion to the attached power cable. Moreover the frequency of response will be at the wave period (linear case) leading to considerable cyclic effects. At present the loading regime in such applications is not well understood, due to a lack of field experience. The paper describes the parameters and results of a dynamic computational model that investigates the umbilical load conditions for a generic wave energy converter. Two geometric configurations of a double armoured power cable are considered, a catenary and a Lazy Wave shape. The model is set up using the dynamic analysis package OrcaFlex and uses top-end motions measured in 1:20 wave tank tests. While the simple catenary shape experiences high tensional forces at the attachment point and considerable compression, the maximum tensional forces can be significantly reduced and compression is avoided with a Lazy Wave shape. For this configuration the highest tension occurs near the attachment point and at the transition points of the buoyancy section. For the modelled conditions, the power cable accumulated a significant number of tension and bending load cycles, indicating that power cables in floating marine energy applications will operate in a high cycle regime (in the order of  $10^6$  cycles) likely to accumulate several million load cycles during a single year of operation.

WS8.8 DELORM, T. & TAVNER, P.J.: “Reliability methodology for evaluating tidal stream devices”, *Proceeding of the 11<sup>th</sup> International Conference on Applications of Statistics and Probability in Civil Engineering - ICASP'11, Zurich, 1-4 August, 2011*. <http://www.ibk.ethz.ch/fa/icasp11/>

Tidal Stream Devices (TSD) are relatively new and to date only a few prototypes have been operational in the water. Therefore relatively little reliability data has been accumulated. However, increasing pressure to develop reliable sources of renewable electric power is encouraging investors to consider TSDs. There are a variety of tidal stream solutions currently under consideration, including floating tethered, seabed bottom-mounted ducted and seabed pile-mounted turbines, but in the absence of in-service reliability data it is impossible for investors and developers to critically evaluate the comparative reliability of different technologies. This paper proposes a robust methodology, defining TSD reliability block diagrams in a rigorous way, using surrogate data from different industries, to compile and compare TSD failure rates and survivor functions. This methodology has been applied to four different TSDs and interesting conclusions are drawn about the way ahead for future reliable TSD design.

WS8.9 THIES, P.R. & JOHANNING, L.: “Development of a marine component testing facility for marine energy converters”, *Proc. 3rd International Conference on Ocean Energy – ICOE 2010*, 6th – 8th October 2010, Bilbao, Spain. <http://www.icoe2010bilbao.com/ing/index.aspx>

High reliability and availability of marine energy devices are key for successful and viable commercial-scale projects. This paper briefly reviews applicability and uncertainties of available component failure rate data and how reliability importance measures could be used as a tool to identify critical system components. Furthermore two component test facilities currently under development at the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE) group at the University of Exeter are described. The intention is to enable component reliability testing for marine renewable energy converters. The South Western Mooring Test Facility (SWMTF) is a unique mooring load and response test facility, at large scale in real sea condition and has been recently installed. The Dynamic Marine Component Test facility (DMaC) is capable to perform accelerated component testing under simulated in-service field conditions. Those two facilities will allow measuring loads that are experienced in the field through prototype testing at the SWMTF and subsequently replicate those load conditions (or information from device developers) at the DMaC for accelerated reliability testing. The application of component reliability testing can reveal design weaknesses prior to deployment and establish necessary reliability and maintenance information. Components tested under service simulated conditions could be evaluated regarding performance, expected lifetime and subsequently be (cost-) optimised.

WS8.10 VAL, D.V. & CHERNIN, L.: “Reliability of tidal stream turbine blades”, *Proceeding of the 11<sup>th</sup> International Conference on Applications of Statistics and Probability in Civil Engineering - ICASP’11*, Zurich, 1-4 August, 2011. <http://www.ibk.ethz.ch/fa/icasp11/>

Tidal stream turbines are a new technology for extracting kinetic energy from tidal currents. A number of different concepts of such devices have been proposed up to now and the most popular of them is a horizontal-axis turbine with propeller-type blades. Although the concept looks similar to a typical wind turbine, guidelines for the design and reliability assessment of wind turbine blades are not applicable for those of tidal stream turbines due to a number of reasons, in particular much higher loads on the blades of tidal turbines since seawater is about 830 times denser than air. The paper concentrates on the reliability of tidal turbine blades in the context of bending failure. Uncertainties associated with tidal current speeds, the blade resistance and the model used to calculate bending moments in the blades are taken into account in reliability analysis. The paper shows how results of the reliability analysis can be applied to set values of the partial factors for the design of tidal turbine rotor blades with respect to failure in bending.

WS8.11 VAL, D.V., & ILIEV, C.: “Reliability of power train components in tidal stream turbines”, *Proceeding of the 11<sup>th</sup> International Conference on Applications of Statistics and Probability in Civil Engineering - ICASP’11*, Zurich, 1-4 August, 2011. <http://www.ibk.ethz.ch/fa/icasp11/>

Tidal stream turbines extract kinetic energy from tidal streams and convert it into electricity. This is a new technology and lack of historical data causes significant uncertainty in the prediction of performance of these devices. The paper provides a brief description of a typical power train of a tidal stream turbine, including its simple reliability model. A method for assessing failure rates of the power train components is then described. The method is based on a Bayesian approach that uses generic failure data for similar components from other industries to construct a prior distribution. Generic failure data are represented by the base failure rate, which is adjusted to actual operating and environmental conditions of the component

under consideration by applying the so-called “influence” factors. Since there are uncertainties associated with the evaluation of the influence factors, the latter are treated as random variables and the prior distribution of the component failure rate is obtained by Monte Carlo simulation. The posterior distribution is estimated as new information about the component performance in an operating tidal turbine becomes available. The method is illustrated by assessing the failure rate of the main bearing of a tidal turbine power train.

WS8.12 VAL, D.V. & CHERNIN, L.: “Probabilistic evaluation of failure rates of mechanical components in tidal stream turbines”, *9<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC 2011)*, Southampton, 5-9 September, 2011. <http://www.ewtec.org/>

The paper presents a method for estimating failure rates of mechanical components of a drive train in tidal stream turbines. The method is based on a Bayesian approach that uses generic failure data for similar components from other industries to construct a prior distribution. Generic failure data are represented by the base failure rate, which is then adjusted to actual operating and environmental conditions of the component under consideration by multiplying it by the so-called “influence” factors. Uncertainties associated with the evaluation of the base failure rate and the influence factors are treated as random variables and the prior distribution of the component failure rate is obtained by Monte Carlo simulation. A posterior distribution of the failure rate is estimated as new information about the component performance in operating tidal stream turbines becomes available. The proposed method is illustrated by constructing the prior distributions of the failure rate of the drive train components (rolling bearing and mechanical seal) which are then updated in accordance to various scenarios of the component performance.

WS8.13 VAL, D.V. AND CHERNIN, L.: “Reliability-based design of rotor blades in tidal stream turbines”, *9<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC 2011)*, Southampton, 5-9 September, 2011. <http://www.ewtec.org/>

Tidal stream turbines are used for converting kinetic energy of tidal currents into electricity. There are a number of uncertainties involved in the design of such devices and their components. To ensure safety of the turbines these uncertainties must be taken into account. The paper shows how this may be achieved for the design of rotor blades of horizontal-axis tidal stream turbines in the context of bending failure due to extreme loading. Initially, basic concepts of the design of such turbines in general and their blades in particular are briefly described. A probabilistic model of tidal current velocity fluctuations, which are the main source of load uncertainty, is then presented. This is followed by the description of reliability analysis of the blades, which along with the uncertainty associated tidal current velocity takes into account also uncertainties in the blade resistance and the model used to calculate bending moments in the blades. Finally, the paper demonstrates how results of the reliability analysis can be applied to set values of the partial factors for the blade design.

WS8.14 JOHANNING, L., THIES, P.R., PARISH, D., & SMITH, G.H.: “Offshore Reliability approach for floating renewable energy devices”, *Proc. of 30th Int. Conference on Ocean, Offshore and Arctic Engineering (OMAE)*, Manuscript Nr. OMAE2011-49844, 2011  
<http://www.asmeconferences.org/omae2011/>

This paper describes the test facilities developed within the Peninsular Research institution for Marine Renewable Energy (PRIMaRE) group and discusses the approach of the group to mitigate risk for marine renewable energy installations. The main consideration is given to the reliability assessment of components within mooring configurations and towards power umbilical for typical renewable energy sites. Load and response data from sea trial will be used to highlight the importance of these research activities, and a Dynamic Marine Component Test rig (DMaC) is introduced that allows four degree of freedom fatigue or destructive tests. Furthermore it is discussed how this facilities could also aid in the reliability assessment of wider offshore applications.

WS8.15 THIES, P. R., JOHANNING, L. & SMITH G. H.: “Towards component reliability testing for marine energy converters”, *Ocean Engineering*, vol. 38, issue 2-3, (2011), pp. 360–370.  
<http://www.sciencedirect.com/science/article/pii/S0029801810002568>

The dearth of generally available, failure data that can be directly applied to marine energy converters (MECs) has been commented on for some years. The advancement of the industry will be fundamentally linked to proven reliability assessments, which is difficult on an industry wide basis. This paper describes how targeted component reliability testing could enable the establishment of relevant failure rate data for the marine renewable energy industry. The necessity of dedicated component testing is briefly reviewed for the wave energy sector together with the experience from other industries. A generic procedure used in test intensive industries for service simulation testing is outlined and applied to wave tank mooring tests. By means of a rainflow analysis procedure and the Palmgren–Miner rule the most severe load cycles, largely contributing to the fatigue damage are identified and reproduced for a possible component test signal. The application of the suggested generic test approach will assist marine energy stakeholders in obtaining evidence of component reliability under simulated operational conditions much more rapidly than can be achieved with prototypes under normal service conditions. Importantly, this would also allow amore accurate estimate of field failure rates and could reveal possible failure modes/design weaknesses ahead of field deployments.

### ***Accepted and/or In Press***

WS8.16 THIES, P.R., JOHANNING, L., & SMITH, G.H.: “Assessing mechanical loading regimes and fatigue life of marine power cables in marine energy applications”, *Special Issue Proc. of the Institution of Mechanical Engineers, Part O, Journal of Risk and Reliability*, accepted for publication, 2011. <http://pio.sagepub.com/>

Reliable marine power cables are imperative for the cost-effective operation of marine energy conversion systems. There is considerable experience with marine power cables under static and dynamic load conditions but the loading regimes for floating marine energy converters (MECs) are not well understood, due to a lack of field experience.

This paper aims to assess mechanical load conditions and failure modes for a dynamic power cable that is connected to a floating wave energy converter. The applied approach combines experimental tank test data with numerical modelling and site specific wave characteristics to identify maximum load points and to quantify the fatigue life. The effect of varying wave parameters on maximum loads and fatigue cycles is investigated and results are presented for two common umbilical configurations, catenary and lazy wave.

In situations with limited field experience, the presented approach provides a tool to determine if critical components are fit for purpose and to assess the expected level of reliability prior to deployment. The cable conductor’s fatigue life is estimated for the lazy wave configuration and highlights component fatigue failure as a major concern that must be addressed in floating marine energy applications.

WS8.17 DELORM, T. M., Zappalà, D & TAVNER, P.J.: “Tidal stream device reliability comparison models”, *Proc. of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*. <http://pio.sagepub.com/>

Tidal Stream Devices are a new technology for extracting renewable energy from the sea. Various Tidal Stream Device models have been proposed and, if they are installed at chosen high tidal stream velocity sites, they will face extreme climatic, current and wave load conditions. As they contain complex mechanical, electrical, control and structural systems, reliability and survivability will be a challenge. Data on their reliability is currently scant, as only a few prototypes have been built and operated. However, reliability prediction of new devices could minimise risk in undertaking prototype work. A practicable Tidal Stream Device reliability prediction method could assist the development of cost-effective and viable future options. This study proposes such a method and derives system reliability models for four different, generic design, horizontal-axis, Tidal Stream Devices, all rated 1-2 MW. Historical reliability data from similarly-rated wind turbines and other relevant marine databases were used to populate the devised reliability models. The work shows that Tidal Stream Devices can expect to have a lower reliability than Wind Turbines of comparable size and that failure rates increase with complexity. The work also shows that with these rate predictions, few devices can expect to survive in the

water for a year. This suggests that either predicted failure rates must be dramatically reduced or that methods for raising reliability by the use of twin axes or improving maintenance access by unmooring or the use of a sea-bed pile and turbine raising, must achieve better survivor rates. The purpose of this work is not to predict definitive individual device failure rates but to provide a comparison between the reliabilities of a number of different device concepts.

### **WORKSTREAM 9 - Economic analysis of variability and penetration**

- WS9.1 ALLAN, G. J., MCDONALD, J., MCGREGOR, P. G. & SWALES, J. K.: “A distinctive Scottish energy policy?”, *Fraser of Allander Economic Commentary*, June 2008, Vol. 32, No. 1, pp. 46-60. [http://www.strath.ac.uk/media/departments/economics/fairse/backissues/media\\_144845\\_en.pdf](http://www.strath.ac.uk/media/departments/economics/fairse/backissues/media_144845_en.pdf)

This paper explores the emergence of a distinctive energy policy for Scotland and raises the issue of the desirability of any differentiation from UK energy policy. This requires an examination of both UK and Scottish energy policies, although we adopt a rather broad-brush overview rather than a very detailed analysis.

- WS9.2 TURNER, K.: “A computable general equilibrium analysis of the relative price sensitivity required to induce rebound effects in response to an improvement in energy efficiency in the UK economy”, *Strathclyde Discussion Paper in Economics*. 2008  
[http://www.strath.ac.uk/media/departments/economics/researchdiscussionpapers/2008/media\\_140190\\_en.pdf](http://www.strath.ac.uk/media/departments/economics/researchdiscussionpapers/2008/media_140190_en.pdf)

In recent years there has been extensive debate in the energy economics and policy literature on the likely impacts of improvements in energy efficiency. This debate has focussed on the notion of rebound effects. Rebound effects occur when improvements in energy efficiency actually stimulate the direct and indirect demand for energy in production and/or consumption. This phenomenon occurs through the impact of the increased efficiency on the effective, or implicit, price of energy. If demand is stimulated in this way, the anticipated reduction in energy use, and the consequent environmental benefits, will be partially or possibly even more than wholly (in the case of ‘backfire’ effects) offset. A recent report published by the UK House of Lords identifies rebound effects as a plausible explanation as to why recent improvements in energy efficiency in the UK have not translated to reductions in energy demand at the macroeconomic level, but calls for empirical investigation of the factors that govern the extent of such effects.

Undoubtedly the single most important conclusion of recent analysis in the UK, led by the UK Energy Research Centre (UKERC) is that the extent of rebound and backfire effects is always and everywhere an empirical issue. It is simply not possible to determine the degree of rebound and backfire from theoretical considerations alone, notwithstanding the claims of some contributors to the debate. In particular, theoretical analysis cannot rule out backfire. Nor, strictly, can theoretical considerations alone rule out the other limiting case, of zero rebound, that a narrow engineering approach would imply.

In this paper we use a computable general equilibrium (CGE) framework to investigate the conditions under which rebound effects may occur in the Scottish regional and UK national economies. Previous work has suggested that rebound effects will occur even where key elasticities of substitution in production are set close to zero. Here, we carry out a systematic sensitivity analysis, where we gradually introduce relative price sensitivity into the system, focusing in particular on elasticities of substitution in production and trade parameters, in order to determine conditions under which rebound effects become a likely outcome. We find that, while there is positive pressure for rebound effects even where (direct and indirect) demand for energy is very price inelastic, this may be partially or wholly offset by negative income and disinvestment effects, which also occur in response to falling energy prices.

- WS9.3 ALLAN, G. J., BRYDEN, I., MCGREGOR, P. G., STALLARD, T., SWALES, J. K., TURNER, K. & WALLACE, A. R. (2008), “Concurrent and legacy economic and environmental impacts from establishing a marine energy sector in Scotland”, *Energy Policy*, Vol. 36, No. 7, July 2008, pp. 2734-2753.  
<http://www.sciencedirect.com/science/article/pii/S030142150800075X>



We examine the economic and environmental impact that the installation of 3 GW of marine energy capacity would have on Scotland. This is not a forecast, but a projection of the likely effects of meeting the Scottish Government's targets for renewable energy through the development of a marine energy sector. Energy, with a particular focus on renewables, is seen by the Scottish Government as a “key sector”, with high growth potential and the capacity to boost productivity (Scottish Government, 2007a. The Government Economic Strategy. The Scottish Government, Edinburgh). The key nature of this sector has been identified through targets being set for renewable energy to achieve environmental and economic benefits. Using a regional computable general equilibrium (CGE) model of Scotland we show that the development of a marine energy sector can have substantial and beneficial impacts on GDP, employment and the environment over the lifetime of the devices, given the encouragement of strong indigenous inter-industry linkages. Furthermore, there are also substantial “legacy” effects that persist well beyond the design life of the devices.

- WS9.4 MCGREGOR, P. G., SWALES, J. K. & TURNER, K.: “The CO<sub>2</sub> ‘trade balance’ between Scotland and the rest of the UK: Performing a multi-region environmental input-output analysis with limited data”, *Ecological Economics*, Volume 66, Issue 4, 15 July 2008, Pages 662-673, ISSN 0921-8009, 10.1016/j.ecolecon.2007.11.001.  
<http://www.sciencedirect.com/science/article/pii/S0921800907005265>

In this paper we attempt an empirical application of the multi-region input-output (MRIO) method proposed by Turner, Lenzen, Wiedmann and Barrett [Turner, K., Lenzen, M., Wiedmann, T., Barrett, J., 2007. Examining the global environmental impact of regional consumption activities -- part 1: a technical note on combining input-output and ecological footprint analysis. *Ecological Economics* 62 (1), 37-44] in a recent issue of this journal in order to enumerate the CO<sub>2</sub> pollution content of interregional trade flows between Scotland and the rest of the UK (RUK). We extend the analysis to account for direct emissions generation by households, as final consumers, and to a social accounting matrix (SAM), where a more comprehensive account of incomes and expenditures is possible. While the existence of significant data problems mean that the quantitative results of this study should be regarded as provisional, the interregional economy-environment IO and SAM framework for Scotland and RUK allows an illustrative analysis of some very important issues in terms of the nature and significance of interregional environmental spillovers within the UK and the existence of a CO<sub>2</sub> 'trade balance' between Scotland and RUK.

- WS9.5 TURNER, K.: “Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK Economy”, *Energy Economics*, Volume 31, Issue 5, September 2009, Pages 648-666, ISSN 0140-9883, DOI: 10.1016/j.eneco.2009.01.008.  
<http://www.sciencedirect.com/science/article/pii/S0140988309000127>

This paper uses a computable general equilibrium (CGE) framework to investigate the conditions under which rebound effects may occur in response to increases in energy efficiency in the UK national economy. Previous work for the UK has suggested that rebound effects will occur even where key elasticities of substitution in production are set close to zero. The research reported in this paper involves carrying out a systematic sensitivity analysis, where relative price sensitivity is gradually introduced into the system, focusing specifically on elasticities of substitution in production and trade parameters, in order to determine conditions under which rebound effects become a likely outcome. The main result is that, while there is positive pressure for rebound effects even where (direct and indirect) demands for energy are very price inelastic, this may be partially or wholly offset by negative income, competitiveness and disinvestment effects, which also occur in response to falling energy price. The occurrence of disinvestment effects is of particular interest. These occur where falling energy prices reduce profitability in domestic energy supply sectors, leading to a contraction in capital stock in these sectors, which may in turn lead to rebound effects that are smaller in the long run than in the short run, a result that runs contrary to the predictions of previous theoretical work in this area.

- WS9.6 TURNER, K. & ANSON, S. (2009), “Rebound and disinvestment effects in oil consumption and supply resulting from an increase in energy efficiency in the Scottish commercial transport sector”, *Energy Policy*, Vol. 37, pp. 3608-3620.  
<http://www.sciencedirect.com/science/article/pii/S0301421509002705>

In this paper we use an energy-economy-environment computable general equilibrium (CGE) model of the Scottish economy to examine the impacts of an exogenous increase in energy augmenting technological progress in the domestic commercial Transport sector on the supply and use of energy. We focus our analysis on oil, as the main type of energy input used in commercial transport activity. We find that a 5% increase in energy efficiency in the commercial Transport sector leads to rebound effects in the use of oil-based energy commodities in all time periods, in the target sector and at the economy-wide level. However, our results also suggest that such an efficiency improvement may cause a contraction in capacity in the Scottish oil supply sector. This 'disinvestment effect' acts as a constraint on the size of rebound effects. However, the magnitude of rebound effects and presence of the disinvestment effect in the simulations conducted here are sensitive to the specification of key elasticities of substitution in the nested production function for the target sector, particularly the substitutability of energy for non-energy intermediate inputs to production.

- WS9.7 TURNER, K. & HANLEY, N. (2009), "How do improvements in labour productivity in the Scottish economy affect the UK position on the environmental Kuznets curve?", *Strathclyde Discussion Paper in Economics*, No. 09-15, <http://www.strath.ac.uk/media/departments/economics/researchdiscussionpapers/2009/09-15KT.pdf>

The Environmental Kuznets Curve (EKC) hypothesis focuses on the argument that rising prosperity will eventually be accompanied by falling pollution levels as a result of one or more of three factors: (1) structural change in the economy; (2) demand for environmental quality increasing at a more-than-proportional rate; (3) technological progress. Here, we focus on the third of these. In previous work we have used single region/nation models of the Scottish and UK economies to simulate the impacts of increased labour and energy efficiency on the domestic economy's position on the EKC, with a specific focus on CO<sub>2</sub> emissions. There we find that, while the impacts of an increase in energy efficiency are difficult to predict, mainly due to the potential for 'rebound' effects, while increasing CO<sub>2</sub> emissions, improved labour productivity is likely to move an economy along its EKC through more rapid GDP growth. However, recent developments in the EKC literature have raised the issue of whether this will still be the case if emissions are accounted for from a consumption rather than a production perspective (the 'pollution leakage' hypothesis) – i.e. taking account of indirect pollution generation embodied in trade flows rather than just domestic emissions generation. Here we extend our earlier single region analysis for Scotland by using an interregional CGE model of the UK economy to examine the likely impacts of an increase in Scottish labour productivity on the rest of the UK and on a national EKC through interregional labour migration and trade flows.

- WS9.8 TURNER, K. (2008), "How can we measure Scotland's footprint? (and, once we have, what do we do with it?)", *Fraser of Allander Economic Commentary*, November 2008, Vol. 32, No. 2, pp.47-51. [http://www.strath.ac.uk/media/departments/economics/fairse/fecs/Final\\_FEC\\_Vol\\_32\\_No\\_2.pdf](http://www.strath.ac.uk/media/departments/economics/fairse/fecs/Final_FEC_Vol_32_No_2.pdf)

This article focuses on the environmental and carbon accounting in Scotland in general, and the calculation and use of ecological and carbon footprints in particular.

- WS9.9 ALLAN, G., AULT, G., MCGREGOR, P. G. & SWALES, J. K.: "The importance of revenue sharing for the local economic impacts of a renewable energy project: A social accounting matrix approach", *Strathclyde Discussion Paper in Economics*, No. 08-11, 2008. <http://www.strath.ac.uk/media/departments/economics/researchdiscussionpapers/2008/08-11strathecon.pdf>

As demand for electricity from renewable energy sources grows, there is increasing interest, and public and financial support, for local communities to become involved in the development of renewable energy projects. In the UK, "Community Benefit" payments are the most common financial link between renewable energy projects and local communities. These are "goodwill" payments from the project developer for the community to spend as it wishes. However, if an ownership stake in the renewable energy project were possible, receipts to the local community would potentially be considerably higher. The local economic impacts of these receipts are difficult to quantify using traditional Input-Output

techniques, but can be more appropriately handled within a Social Accounting Matrix (SAM) framework where income flows between agents can be traced in detail. We use a SAM for the Shetland Islands to evaluate the potential local economic and employment impact of a large onshore wind energy project proposed for the Islands. Sensitivity analysis is used to show how the local impact varies with: the level of Community Benefit payments; the portion of intermediate inputs being sourced from within the local economy; and the level of any local community ownership of the project. By a substantial margin, local ownership confers the greatest economic impacts for the local community.

- WS9.10 HANLEY, N., MCGREGOR, P. G., SWALES, J. K. & TURNER, K.: “Do increases in energy efficiency improve environmental quality and sustainability?”, *Ecological Economics*, Volume 68, Issue 3, 15 January 2009, Pages 692-709, ISSN 0921-8009, DOI: 10.1016/j.ecolecon.2008.06.004  
<http://www.sciencedirect.com/science/article/pii/S0921800908002589>

Governments world-wide increasingly see energy efficiency as an important aspect of sustainability. However, there is a debate in the literature as to whether the impact of improved energy efficiency on reducing energy use might be partially, or more than wholly, offset through “rebound” and “backfire” effects. This paper clarifies the theoretical conditions under which such effects would occur and explores their likely significance using a computable general equilibrium (CGE) model of the Scottish economy. We find that for Scotland a general improvement in energy efficiency in the production sectors of the economy initially produces rebound effects that eventually grow into backfire. Energy use ultimately increases in response to an efficiency gain and the ratio of GDP to CO<sub>2</sub> emissions falls. The economic factors underpinning rebound effects are straightforward: energy efficiency improvements result in an effective cut in energy prices, which produces output, substitution, competitiveness and income effects that stimulate energy demands. However, the presence of strong rebound or even backfire does not mean that efficiency-enhancing policies are irrelevant: rather it suggests that such policies operating alone are insufficient to generate environmental improvements. The implication is that a co-ordinated portfolio of energy policies is required.

- WS9.11 WILSON, I. A. G., MCGREGOR, P. G. & HALL, P. J.: “Energy storage in the UK electrical network: Estimation of the scale and review of technology options”, *Energy Policy*, Vol. 38, No. 8 (2010), pp. 4099-4106.  
[http://www.florence-school.eu/portal/page/portal/LDP\\_HOME/Events/Projects\\_Series/Energy%20Net\\_Regulation%20%20CCP/Second\\_Workshop/Wilson.pdf](http://www.florence-school.eu/portal/page/portal/LDP_HOME/Events/Projects_Series/Energy%20Net_Regulation%20%20CCP/Second_Workshop/Wilson.pdf)

This paper aims to clarify the difference between stores of energy in the form of non-rechargeable stores of energy such as fossil-fuels, and the storage of electricity by devices that are rechargeable. The existing scale of these two distinct types of storage is considered in the UK context, followed by a review of rechargeable technology options. The storage is found to be overwhelmingly contained within the fossil-fuel stores of conventional generators, but their scale is thought to be determined by the risks associated with long supply chains and price variability. The paper also aims to add to the debate regarding the need to have more flexible supply and demand available within the UK electrical network in order to balance the expected increase of wind derived generation. We conclude that the decarbonisation challenge facing the UK electricity sector should be seen not only as a supply and demand challenge but also as a storage challenge.

- WS9.12 ALLAN, G., EROMENKO, I., MCGREGOR, P. & SWALES, K.: “The regional electricity generation mix in Scotland: A portfolio selection approach incorporating marine technologies”, *Energy Policy*, Volume 39, Issue 1, January 2011, Pages 6-22, ISSN 0301-4215, 10.1016/j.enpol.2010.08.028. <http://www.sciencedirect.com/science/article/pii/S0301421510006439>

Standalone levelised cost assessments of electricity supply options miss an important contribution that renewable and non-fossil fuel technologies can make to the electricity portfolio: that of reducing the variability of electricity costs, and their potentially damaging impact upon economic activity. Portfolio theory applications to the electricity generation mix have shown that renewable technologies, their costs being largely uncorrelated with non-renewable technologies, can offer such benefits. We look at the existing Scottish generation mix and examine drivers of changes out to 2020. We assess recent scenarios

for the Scottish generation mix in 2020 against mean-variance *efficient* portfolios of electricity-generating technologies. Each of the scenarios studied implies a portfolio cost of electricity that is between 22% and 38% higher than the portfolio cost of electricity in 2007. These scenarios prove to be mean-variance “inefficient” in the sense that, for example, lower variance portfolios can be obtained without increasing portfolio costs, typically by expanding the share of renewables. As part of extensive sensitivity analysis, we find that Wave and Tidal technologies can contribute to lower risk electricity portfolios, while not increasing portfolio cost.

- WS9.13 ALLAN, G., GILMARTIN, M., MCGREGOR, P. & SWALES, K. :“Levelised costs of wave and tidal energy in the UK: Cost competitiveness and the importance of “banded” Renewables Obligation Certificates”, *Energy Policy, Volume 39, Issue 1, January 2011, Pages 23-39, ISSN 0301-4215*, DOI: 10.1016/j.enpol.2010.08.029.  
<http://www.sciencedirect.com/science/article/pii/S0301421510006440>

In this paper, publicly available cost data are used to calculate the private levelised costs of two marine energy technologies for UK electricity generation: Wave and Tidal Stream power. These estimates are compared to those for ten other electricity generation technologies whose costs were identified by the UK Government (DTI, 2006). Under plausible assumptions for costs and performance, point estimates of the levelised costs of Wave and Tidal Stream generation are £190 and £81/MWh, respectively. Sensitivity analysis shows how these relative private levelised costs calculations are affected by variation in key parameters, specifically the assumed capital costs, fuel costs and the discount rate. We also consider the impact of the introduction of technology-differentiated financial support for renewable energy on the cost competitiveness of Wave and Tidal Stream power. Further, we compare the impact of the current UK government support level to the more generous degree of assistance for marine technologies that is proposed by the Scottish government.

- WS9.14 ALLAN, G. J., MCGREGOR, P. G., & SWALES, J. K: “The electricity generation mix in Scotland: The long and windy road?”, with Peter McGregor and Kim Swales, *Fraser Economic Commentary*, Special Issue No. 1 – Energy and pollution, January 2011, pp. 62-72.  
[http://www.strath.ac.uk/media/departments/economics/fairse/specialissues/Special\\_Issue\\_No\\_1\\_-\\_Energy\\_&\\_Pollution\\_-\\_Jan\\_2011.pdf](http://www.strath.ac.uk/media/departments/economics/fairse/specialissues/Special_Issue_No_1_-_Energy_&_Pollution_-_Jan_2011.pdf)
- WS9.15 MCGREGOR, P. G., SWALES, J. K& WINNING, M.: “Scottish climate change policy: An overview”, *Fraser Economic Commentary*, Special Issue No. 1 – Energy and pollution, January 2011, pp. 27-34.  
[http://www.strath.ac.uk/media/departments/economics/fairse/specialissues/Special\\_Issue\\_No\\_1\\_-\\_Energy\\_&\\_Pollution\\_-\\_Jan\\_2011.pdf](http://www.strath.ac.uk/media/departments/economics/fairse/specialissues/Special_Issue_No_1_-_Energy_&_Pollution_-_Jan_2011.pdf)
- WS9.16 WILSON, G., MCGREGOR, P. G., INFIELDS, D., & HALL, P. “Grid-connected renewables, storage and the UK electricity market”, *Renewable Energy, Volume 36, Issue 8, August 2011, Pages 2166-2170, ISSN 0960-1481*, DOI: 10.1016/j.renene.2011.01.007.  
<http://www.sciencedirect.com/science/article/pii/S0960148111000139>

This article is mainly a counterpoint to an article by Swift-Hook in the journal of Renewable Energy titled “Grid-connected intermittent renewables are the last to be stored”. It also describes the four main distinct UK markets where electrical energy and services are traded, in order to provide a context for the discussion of renewable energy and energy storage in the UK electricity system. In Swift-Hook’s article it was argued that “grid-connected intermittent renewables like wind energy will never be stored unless nothing else is available” and that “storage is counter-productive for fuel saving”. We, however, find evidence that “grid-connected intermittent renewables” have been, and will continue to be stored when it suits the “UK market” to do so. Furthermore, Swift-Hook’s article neglects the potential wider benefits that storage offers to UK energy policy’s goals, in terms of reduced emissions (when used in conjunction with renewables) and enhanced security of supply.

- WS9.17 TURNER, K. & HANLEY, N.: “Energy efficiency, rebound effects and the environmental Kuznets curve”, *Energy Economics. Volume 33, Issue 5, September 2011, Pages 709-720, ISSN 0140-9883*, 10.1016/j.eneco.2010.12.002.  
<http://www.sciencedirect.com/science/article/pii/S0140988310002070>

Technological change is one factor used to justify the existence of an Environmental Kuznets Curve, and technological improvements have been argued to be a key factor in mitigating the impacts of economic growth on environmental quality. In this paper we use a CGE model of the Scottish economy to consider the factors influencing the impacts of one form of technological change—improvements in energy efficiency—on absolute levels of CO<sub>2</sub> emissions, on the carbon intensity of the economy (CO<sub>2</sub> emissions relative to real GDP), and the per capita EKC relationship. These factors include the elasticity of substitution between energy and non-energy inputs, responses in the labour market and the structure of the economy. Our results demonstrate the key role played by the general equilibrium price elasticity of demand for energy, and the relative influence of different factors on this parameter.

### *Accepted and/or In Press*

- WS9.18 TURNER, K., GILMARTIN, M., MCGREGOR, P., & SWALES, K.: “An integrated IO and CGE approach to analysing changes in environmental trade balances”. *Papers in Regional Science* (online April 2011; doi:10.1111/j.1435-5957.2011.00365.x).  
<http://onlinelibrary.wiley.com/doi/10.1111/j.1435-5957.2011.00365.x/abstract>

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- WS9.19 GILMARTIN, M., & KOROBILIS, D. “On regional unemployment: An empirical examination of the determinants of geographical differentials in the UK”, Forthcoming in *Scottish Journal of Political Economy*. <http://www.blackwellpublishing.com/journal.asp?ref=0036-9292>

In this paper we consider the determinants of regional disparities in unemployment rates for the UK regions at NUTS-II level. We use a mixture panel data model to describe unemployment differentials between heterogeneous groups of regions. The results indicate the existence of two clusters of regions in the UK economy, characterised by high and low unemployment rates respectively. A major source of heterogeneity appears to be caused by the varying effect (between the two clusters) of the share of employment in the service sector, and we trace its origin to the fact that the high unemployment cluster is characterised by a higher degree of urbanization.

- WS9.20 LECCA, P., SWALES, J.K., & TURNER, K.: “An investigation of issues relating to where energy should enter the production function”, Forthcoming in *Economic Modelling*. 2011  
<http://www.management.stir.ac.uk/research/economics/?a=21175>

This paper examines the impact of imposing different separability assumptions in the specifications of the standard hierarchical KLEM production function in a computable general equilibrium (CGE) model. The appropriate means of introducing energy to sectoral production functions in CGE models has been a source of debate for a number of years. However, while modellers often subject their model results to sensitivity analysis with respect to the values associated with elasticities of substitution between inputs, it is rarely the case that the structure of the production function is subjected to testing. However, the chosen structure reflects the modeller's view about elasticity between different inputs and will have implications for model results wherever there are changes in relative prices. We illustrate our argument by introducing a simple demand shock to a CGE model of the Scottish economy (targetted at the energy supply sector) under different assumptions regarding the structure of the KLEM production function and separability assumptions therein. Specifically, we conduct both systematic and random parameter variation within alternative KLEM production structures, examining the impacts on a number of model outputs, though with primary focus on energy use in production. We find that if energy is introduced to the value-added

rather than intermediates nest there is greater variation in energy use in production in response to the demand disturbance.

### WORKSTREAM 10 - Ecological Consequences of Tidal & Wave Energy Conversion

WS10.1 SHIELDS, M., PANDIAN, P. K., SIDE, J., GIBB, S., HARRIS, R., KERR, S., WOOLF, D. & OSALUSI, E., (2008), "A multidisciplinary approach to advancing marine renewable energy research in Scotland", A poster presented at the *International Conference on Ocean Energy* (ICOE 2008), Brest, France, 15 – 17 October 2008. <http://www.icoe2008.com/>

Generating electricity from wave and tidal energy resources within Scottish waters could provide Scotland with a sustainable source of energy. Within UK waters the extractable potential of wave and tidal energy has been estimated at about 58 TWh per year, with the majority of this resource located in Scottish waters. The Scottish Government has recognised this potential resource and is fully committed to promoting the increased use of renewables to tackle climate change and for the economic benefit of Scotland. In this context, the Strategic Research Development Grant (SRDG) entitled 'Advancing Marine Renewable Energy Research in Scotland' aims to remove a key sectoral roadblock to UK marine renewables development. Four major themes will be addressed and include coastal physical processes, hydrodynamics and water column processes, benthic-pelagic dynamics and ecological considerations and process. In this poster, an overview of each of the research themes is presented along with preliminary findings from coastal physical processes and benthic-pelagic dynamics in and around the Pentland Firth, Scotland. This SRDG study will focus on developing an understanding of environmental impacts, build research capacity and contribute to 'Marine Renewable Energy Development in Scotland'.

WS10.2 SAVIDGE, G.: "The SeaGen tidal turbine: the Environmental Monitoring Programme", 2<sup>nd</sup> *International Conference on Ocean Energy – ICOE 2008*, Brest, France. <http://www.icoe2008.com/>

The 1.2 MW SeaGen tidal turbine was installed in Strangford Narrows, County Down, Northern Ireland in April 2008. Maximum current speeds in the Narrows are of the order of 4 ms<sup>-1</sup> and the tidal range is approximately 3.5m. The Narrows are a designated SAC and consequently the local Environmental Regulator required the development and initiation of an extensive and detailed environmental monitoring programme before the necessary installation licence could be issued. A brief overview of the installation of the turbine will be presented together with a review of the ongoing environmental monitoring programme. Emphasis is placed on the monitoring of the status and activity of the local Common (Harbour) Seal population and also on the benthos. The ecological observations are supported by detailed ADCP current measurements and examples of the current vector distributions will also be presented.

WS10.3 SAVIDGE, G.: "Environmental effects of new water power technologies: what we know and what we are learning", *Hydrovision 2008*, Sacramento, USA. <http://hcistore.com/hydrovision/index.asp>

WS10.4 OSALUSI, E., SIDE, J. & HARRIS, R.: "Reynolds stress and turbulence estimates in bottom boundary layer of Fall of Warness", *International Communications in Heat and Mass Transfer*, vol. 36, issue 5, (2009), pp. 412–421. <http://www.sciencedirect.com/science/article/pii/S073519330900044X>

The first of two studies (see also below) based on ADCP data for the European Marine Energy Centre's tidal test site. A broadband Acoustic Doppler Current Profiler (ADCP) moored on the seabed at 42 m depth was used to observe the mean and turbulent flow components in the tidally energetic Fall of Warness channel over two tidal cycles. The Reynolds stress was estimated from the difference in variance between the along-beam velocities of opposing acoustic beams. Near bed stress at 2.63 m above seabed exceeds 7.5Pa at the time of mean flow. Turbulent Kinetic Energy (TKE) density, the rates of TKE production and dissipation, and eddy viscosity were evaluated using the variance method. Depth–time variations of turbulence in the channel are revealed from the analysis of ADCP measurements. The work defines important features of turbulence in unstratified tidal flows.

WS10.5 OSALUSI, E., SIDE, J. & HARRIS, R.: “Structure of turbulent flow in EMEC's tidal energy test site”, *International Communications in Heat and Mass Transfer*, vol. 36, issue 5, (2009), pp. 422–431. <http://www.sciencedirect.com/science/article/pii/S0735193309000530>

The second of two studies (see also above) based on ADCP data for the European Marine Energy Centre's tidal test site. Results from this and that reported above are of great importance to the deployment of marine energy devices in energetic tidal environments. The velocity of the flow at a given location can vary greatly across the actuator area of the turbine, leading to significant variations in loading across the actuator with associated fatigue and vibration problems. Understanding the turbulence levels and flow structure are important not only to the siting of individual units, but can also inform the device design and are important to setting realistic limits to turbine design.

WS10.6 PANDIAN, P. K., RUSCOE, J. P., SHIELDS, M., SIDE, J., HARRIS, R. E., KERR, S. A. & BULLEN C. R.: “Seabed habitat mapping techniques: an overview of the performance of various systems”, *Mediterranean Marine Science*, vol. 10, issue 2, (2009), pp. 29–43. [http://www.medit-mar-sc.net/files/200911/24-131152Medit.Mar.Sci.Vol10\\_num2\\_Dec2009\\_pp29-43\\_PANDIAN\\_337.pdf](http://www.medit-mar-sc.net/files/200911/24-131152Medit.Mar.Sci.Vol10_num2_Dec2009_pp29-43_PANDIAN_337.pdf)

Seabed mapping has become vital for effective management of marine resources. An important role in moving towards ecosystem based management is played by the defining and understanding of the relationships among marine habitat characteristics, species distribution and human activities. Seabed maps are essential for the siting of bottom mounted energy devices, for moorings and also in the longer term for the monitoring of change as a consequence of the extraction of hydrokinetic energy. Mapping seabed characteristics by means of remote acoustic sensing, using seabed seismic profiling, sidescan sonar, or echo-sounder based classification systems, is becoming of increasing importance. This paper gives a brief overview of existing marine habitat mapping technologies and their recent developments. The limitations and constraints of each are investigated in this context, as well as their possible use in combination.

WS10.7 BELL, M. C., SIDE, J., KERR, S., JOHNSON, K. R., BASTON, S. & BULLEN, C. R.: “The emergence of a new marine renewable energy industry – what are the implications for fisheries?”, *International Council for the Exploration of the Sea, Annual Science Conference (ICES CM 2010)*, 20-24 September 2010, Nantes, France. <http://www.ices.dk/indexfla.asp>

In the light of increasing global energy demands and the need to reduce greenhouse gas emissions, attention has recently turned to the sea as a large and renewable source of kinetic energy. Developments for wave and tidal energy extraction currently exist more in potential than in actuality, but there is huge impetus from political, environmental and commercial interest groups for rapid growth of the marine renewable energy sector over the immediate future. Such growth will inevitably have repercussions for other stakeholders in the marine environment. Concerns from fishery interests are likely to centre on access to fishing grounds and on changes to the physical structure and ecological functioning of fish habitats. We examine the extent to which fishery and marine energy resources overlap in UK waters. We also consider in more general terms how marine spatial planning decisions may affect fishery yield and the spawning potential of target stocks. Results of these analyses point to the conclusion that the greatest potential for interaction between the marine energy and fishery sectors is at a local scale in inshore environments. The potential near-field and far-field environmental effects of energy conversion devices, and their repercussions for marine productivity are as yet poorly understood. Marine spatial planning decisions need to be informed by both ecological and socio-economic considerations.

WS10.8 PANDIAN, P. K., OSALUSI, E., RUSCOE, J. P., SIDE, J., HARRIS, R. E., KERR, S. A. & BULLEN C. R.: “An overview of recent technologies on wave and current measurement in coastal and marine applications”, *Journal of Oceanography and Marine Science*, vol. 1, issue 1, (2010), pp. 1–10. <http://www.academicjournals.org/JOMS/PDF/Pdf2010/Jan/Pandian%20et%20al.pdf>

The coastal ocean is the most important zone for the maritime countries for recreation, mineral and energy exploitation, weather forecasting and national security. Understanding of coastal and oceanic processes is mostly based on field measurements and laboratory experiments. Most coastal processes

occur over relatively long time spans and have large spatial extents. They also involve or are impacted by a variety of factors such as waves, wind, tide, storm surges, currents, beach sediment properties, etc. Measurements of waves, both on site and in wave flumes, are carried out using different techniques. This article reviews the different technologies available and presently adopted in wave and current measurements. Different instruments for wave and current measurement have its own advantages and disadvantages depending on the applications and needs. A detailed overview of various studies carried out in worldwide locations on wave and current measurements is presented. Various instruments, their application, advantages, disadvantages and accuracy are discussed in this article. It is essential to choose the type of instrument most appropriate to the application, based on the requirements, necessitating a thorough knowledge of the instruments available, the funding and duration of the project.

WS10.9 SHIELDS, M. A., WOOLF, D. K., GRIST, E. P. M., KERR, S. A., JACKSON, A. C., HARRIS, R. E., BELL, M. C., BEHARIE, R., WANT, A., OSALUSI, E., GIBB, S. W. & SIDE, J.: "Marine renewable energy: The ecological implications of altering the hydrodynamics of the marine environment", *Ocean & Coastal Management*, vol. 54, issue 1, (2011), pp. 2–9.  
<http://www.sciencedirect.com/science/article/pii/S0964569110001924>

Many countries now recognise the need for mitigation of climate change induced by human activities and have incorporated renewable energy resources within their energy policy. There are extensive resources of renewable energy within the marine environment and increasing interest in extracting energy from locations with either large tidal range, rapid flow with and without wave interaction, or large wave resources. However, the ecological implications of altering the hydrodynamics of the marine environment are poorly understood. Ecological data for areas targeted for marine renewable developments are often limited, not least because of the considerable challenges to sampling in high energy environments. In order to predict the scale and nature of ecological implications there is a need for greater understanding of the distribution and extent of the renewable energy resource and in turn, of how marine renewable energy installations (MREIs) may alter energy in the environment. Regional ecological implications of a MREI need to be considered against the greater and global ecological threat of climate change. Finally, it is recommended that the identification of species and biotopes susceptible to the removal of hydrokinetic energy could be a suitable strategy for understanding how a MREI may alter flow conditions.

WS10.10 KENNEDY, R. & SAVIDGE, G.: "Benthic monitoring in Strangford Lough Narrows in relation to the installation of the Seagen tidal turbine". *ICES Annual Science Conference*, Gdańsk, Poland, 19 – 23 September 2011. <http://www.ices.dk/iceswork/asc/2011/index.asp>

A SeaGen tidal turbine was installed in Strangford Narrows in 2008. As part of the associated ecological assessment, epifaunal feeding communities present on tide-swept reefs in the Narrows were surveyed. Four stations were sampled by video quadrat: a reference station and three impact stations along the axis of the Narrows. One pre-installation and four post-installation surveys have been carried out as of April 2011. The epifaunal communities of Strangford Narrows conform to EUNIS biotopes encompassed by CR.HCR.FaT Very tide-swept faunal communities. The stations sampled in the baseline survey were strongly differentiated and only overlapped occasionally by community composition with their nearest neighbours. This pattern was maintained throughout the sampling programme, though there was a seasonal shift in the communities in summer. The relative distribution of the stations in March 2008, March 2009 and April 2010 was very similar. In this very high energy area, there appears to be no significant deleterious effect of the turbine installation. The three year period of monitoring up to this point while the current turbine is operating at a very low level of activity will provide a good baseline against which to assess future changes when the turbine becomes fully operational. Another project to determine the successional change in communities in relation to distance from the most high energy area of the Narrows commenced in 2011 using multibeam acoustic survey, current modelling, and drop-down video assessment of community structure. The outputs of this project may inform managers on the likely effects of the harvesting of kinetic energy from tidal flows in other, less optimal locations.

WS10.11 KENNEDY, R. & SAVIDGE, G.: "The effect of a marine tidal turbine on the epifaunal communities of tide-swept boulders". *World Conference on Marine Biodiversity*, Aberdeen, 26-30 September 2011. <http://www.marine-biodiversity.org/>



The 1.2 MW SeaGen tidal turbine is located in a narrow channel in Northern Ireland linking the large saline embayment of Strangford Lough to the open waters of the Irish Sea. Maximum current speeds in the channel are  $>5 \text{ m s}^{-1}$  with the seabed characterised by tide-swept boulders typical of such high velocity areas. The associated biotope is described in the EUNIS habitat classification scheme (CR.HCR.FaT Very tide-swept faunal communities). The study describes results from the baseline and monitoring stages of the monitoring programme initiated to assess the effects of on the benthic community arising from modification of the ambient flow field by SeaGen. Very little data concerning the variability and the effects of disturbance on the biotope were known prior to the study.

The faunal communities downstream of SeaGen showed strong seasonality and spatial structure, but net changes in community structure following the commencement of operation of Seagen were within the natural variability recorded in the area. A substantial baseline has been obtained that can be used to determine the effect of sustained turbine operation in the future. The study has provided a strong basis for more detailed multidisciplinary follow-up research.

WS10.12 BELL, M. C. & SIDE, J.: “Environmental impacts of tidal and wave power developments and key issues for consideration by environment agencies.” *Background Report on Task 2 of Sniffer ER20. Scotland and Northern Ireland Forum For Environmental Research*, Edinburgh, 2011. <http://www.sniffer.org.uk/>

Renewable energy technologies are commonly seen as a panacea for the environmental problems associated with power generation, not just in terms of greenhouse gas emissions but also by virtue of other impacts such as pollution and habitat destruction. This may well be true of wave and tidal energy developments, but the fact is that there are few direct observations from which to judge the nature and scale of impacts, partly because of the emergent state of the industry, but also because research into this field has tended to focus instead on the nature of the resource and on the engineering aspects of exploiting it. Nevertheless, we can draw inferences about potential impacts based on experience from other industries coupled with knowledge on the vulnerabilities of particular species and habitats and about the inter-relatedness of physical and ecological processes. We can distinguish several different types of interaction including: energy extraction impinging upon natural processes; operational effects on marine biota, acting through device operation, maintenance and decommissioning; provision of new ecological space through the physical presence of devices and other development structures; and displacement of other human activities, modifying the locus and nature of their impacts. The least attention has so far been paid to the first of these aspects, particularly in terms of intervention in physical processes. For this reason, this paper places particular emphasis on the previously under-reviewed topic of potential impacts on physical processes, the more so because many other potential impacts stem from the physical impacts as first causes. We pull together the first comprehensive review of the potential for wave and tidal energy extraction to impinge upon physical processes in the near- and far-fields of developments, before going on briefly to examine the implications for ecological processes. Operational effects are considered mainly in terms of noise and collision risk; pollution risk involving release of oil and chemicals is probably fairly low, and is a general risk for human activities at sea rather than being particular to wave and tidal energy extraction. Changes to ecological space are considered in terms of reef effects and structures functioning as fish aggregation devices. Finally, we focus on marine fishing as the principal interaction with other sea users that is likely to have environmental implications.

WS10.13 BELL, M. C., BULLEN, C., JOHNSON, K. & SIDE, J.: “Overview of political and economic context, and future projections for the size of the industry in the UK.” *Background Report on Task 1 of Sniffer ER20. Scotland and Northern Ireland Forum For Environmental Research*, Edinburgh, 2011. <http://www.sniffer.org.uk/>

This briefing paper looks at the range of developmental targets being adopted for wave and tide renewables by the UK and Scottish Governments including the nature of the wave and tidal resource, policy incentives, and legislative frameworks. It also looks at the emerging role of statutory Marine Spatial Planning (MSP) in helping to organise the use of marine space. Following a brief summary of currently emerging technologies, it reviews a number of key industry roadmaps which seek to predict future development scenarios for the marine renewables sector.

WS10.14 SIDE, J. & BEHARIE, R.: “Sources of underwater noise and disturbance arising from marine renewables developments.” *Proceedings of the International Council for the Exploration of the Sea Annual Science Conference (ICES CM 2011 / S:09)*. 19 -23 September 2011, Gdansk, Poland <http://www.ices.dk/iceswork/asc/2011/index.asp>

Anthropogenic underwater noise has received increasing attention in recent years and is one of the EU Marine Strategy Framework Directive’s descriptors of good environmental status. Wave and tidal energy projects pose new challenges and have required a variety of installation methods where the disturbance arising from sources of underwater noise are only now being considered. The paper reviews the sources of underwater noise associated with the development of this new sector and the methods and studies conducted to date to determine noise levels. Sources of underwater noise arising from the deployment of marine renewables devices are compared with background and other sources of anthropogenic noise in the marine environment. We examine the models used for transmission loss and the present thresholds that are applied to the disturbance of marine mammals in the vicinity, highlighting those sources of most concern and suggesting methods of mitigation.

WS10.15 WANT, A., BELL, M., & SIDE, J.: “Monitoring Marine Habitats of West Mainland Orkney: will Wave Energy Extraction Contribute to Long-Term Change?” *Proceedings of the International Council for the Exploration of the Sea Annual Science Conference (ICES CM 2011 / S:09)*. 19 - 23 September 2011, Gdansk, Poland <http://www.ices.dk/iceswork/asc/2011/index.asp>

Wave energy exposure is an important factor in determining community structure on rocky shorelines. Energy extraction by wave energy converting devices (WECs) might be expected to modify exposure characteristics shoreward of their location. In addition, it is assumed that increased sea temperature, as one component of observed global climatic change will also alter the composition of species on the rocky shore. Determining the relative roles played by concurrent environmental variables (i.e. energy exposure and sea temperature), as well as seasonal and other variables, will be challenging. Littoral and sublittoral monitoring of sentinel species can be used to detect wider ecological trends. Candidate species should be adapted to specific exposure levels, be potentially located at or near their geographical distribution limits, and be sufficiently accessible and prevalent to allow reliable sample collection. Monitoring protocols have been developed for several species on the wave exposed West Mainland of Orkney, an area at the forefront of the developing marine energy sector. Identifying similar species which respond differentially to changes in energy exposure and sea temperature, and monitoring changes in the relationship between these and our sentinel species (such as littoral zone width and height, and abundance), could help discriminate the precise part played by these two important environmental variables. Monitoring procedures include measuring distribution, abundance, density, and growth determination using biometric measurements, quadrat photography, and other sampling techniques on intact and cleared sites. Along with novel image analysis developments, these will provide baseline/control data for this important area.

WS10.16 BELL, M., GRIST, E., ROUSE, S., SPENCE JONES M., PORTER, J., WANT, A., HARRIS, R., & SIDE, J.: “Hydrokinetic energy as an ecological factor – how might wave and tidal energy extraction affect the distribution of marine organisms?” *Proceedings of the International Council for the Exploration of the Sea Annual Science Conference (ICES CM 2011 / S:09)*. 19 -23 September 2011, Gdansk, Poland <http://www.ices.dk/iceswork/asc/2011/index.asp>

Water movements define some of the most important ecological factors determining the distribution of organisms in marine environments. This is true both at large spatial scales, where ecological connectivity and trophic coupling are defined by circulation patterns and vertical mixing structure, and at the much smaller scales at which individual organisms experience flow, turbulence and shear forces. Moving water possesses energy, and this is increasingly regarded as a resource for power generation, potentially meeting 15% of energy demands at a European level by the middle of this century. Conversion of hydrokinetic energy into other forms of energy that are useful for human purposes inevitably involves diversion of physical processes from their ‘natural’ pathways, with possible consequences also for ecological processes. In simple terms, extraction of energy from water flow involves reducing the average velocity of flow and hence changing the conditions experienced by an organism living in the flowing water. In reality, the hydrodynamic consequences of extracting energy are likely to be complex and site-specific, with changes in turbulence as well as both increases and decreases in local flow velocities.

We use statistical models applied to incidence records for marine bryozoan species in Scottish waters to examine the extent to which their distribution may be governed by the same wave and tidal energy variables that influence the location of marine renewable energy developments, and address the question of whether it is possible to predict what might be the consequences of energy extraction for species distribution.

WS10.17 BASTON, S., & HARRIS, R.: “Modelling the Hydrodynamic Characteristics of Tidal Flow in the Pentland Firth.” *Paper No 317 in Proceedings of the 9<sup>th</sup> European Wave and Tidal Energy Conference*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

The recent award of lease rights by The Crown Estate for ‘Round 1’ marine energy development sites in the Pentland Firth and Orkney Waters (PFOW) has focussed the attention of stakeholders on the need for a vastly improved understanding of the local and regional marine environment. The potential environmental intervention effects resulting from ‘extensive’ installation of marine energy devices, necessitates rapid, accurate, baseline environmental assessments to be undertaken. This paper addresses the implementation of the SUNTANS model to simulate the complex flow characteristics in the Pentland Firth. Validation is achieved through comparisons made with field sourced data. A sensitivity analysis of the bottom friction coefficient, which is a parameter required by the model directly related to how much energy is dissipated by seabed friction, is presented along. Results show that the model outputs fit better to field data using a higher value of this parameter than typically assumed, which is sensible because of the size grain of boulders located in the Pentland Firth.

WS10.18 BEHARIE, R.: “Measurements of shoreline wave action to establish possible environmental and ecological effects from wave energy converter arrays.” *Proceedings of the 9<sup>th</sup> European Wave and Tidal Energy Conference*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/>

The distance from shore, operational regime and the variability in the annual downstream shadow effect are key requirements to enable predictions of possible ecological effects on the shoreline. The accepted method of estimating the amount of shoreline wave action or ‘exposure’ to which the rocky shore is subject has been to use quantitative ecological surveys and indicator species vertical range. Difficulties can occur when natural and anthropogenic disturbances have a significant influence on these particular species, fundamentally altering the community structure and spatial distribution, which can result in different assemblages evident even though subject to comparatively similar levels of wave action. To overcome these limitations a new efficient and cost effective device is presented that is able to measure an average quantitative level of wave action over weeks and/or months at the relevant spatial scale of rocky shore biota. This new device will not only enable specific biotopes to be studied in relation to an objective proxy measurement of wave action over biologically meaningful timescales but could also be used, with bathymetry data, for economical evaluations of near-shore wave energy resources in developing nations. Long term monitoring data from Orkney are presented which shows good correlations of significant wave height and direction from concurrent wave buoy data at the European Marine Energy Centre wave test site. Initial measurements have found that habitat and biotope classifications currently used to underpin European protected areas have an over simplistic classification of wave energy levels needed for both accurate comparisons and impact determination between certain rocky shore biotopes. Equivalent rocky shore biotopes classed within the same level of energy are observed to have similar levels during the summer but are subjected to a 2:1 difference in the ratios of wave action in winter.

### ***Accepted and/or In Press***

WS10.19 WANT, A., BELL, M., & SIDE, J.: “Methodologies for the Study of the Ecological Consequences of Wave Energy Extraction on the Rocky Shoreline of Orkney.” *European Marine Biology Symposium*, Edinburgh 25 August 2010 and *Marine Ecology* (in press) <http://embs2010.sls.hw.ac.uk/>

Exposure to wave energy is an important factor in determining the community structure and relative abundance of species found on the rocky shore. Energy extraction by wave energy converting devices (WECs) might be expected to change exposure characteristics shoreward of their location. In addition, it is assumed that rising sea temperatures, as one component of observed global climatic change, will also

alter the composition of species on the rocky shore. Interpretation of observed shifts in community structure following concurrent alterations in both of these two important environmental variables (i.e. energy exposure and sea temperature), as well as seasonal and other variables, will be challenging. Detecting wider ecological trends may be possible by observing population changes in sentinel species. Candidate species for monitoring should be adapted to specific exposure levels, are potentially located at or near their geographical distribution limits, and are sufficiently accessible and prevalent to allow reliable sample collection. Four littoral species have been short-listed for consideration on the wave exposed West Mainland of Orkney: *Chthamalus stellatus*, *Fucus distichus anceps*, *Gibbula umbilicalis*, and *Patella ulyssiponensis*. Identifying similar species which respond differentially to changes in energy exposure and sea temperature, and monitoring changes in the relationship between these and our sentinel species (such as littoral zone width and height, and abundance), could allow for discrimination between the relative roles played by these environmental variables. The selected species are being monitored for distribution, abundance, density, and growth. Sampling regimes include: biometric measurements, quadrat photography, and density determination on intact and cleared sites that will provide baseline/control data for the west coast of Orkney, an important area to the future deployment of this developing technology.

## Patents

Patent 1 (UoE), Mueller & Ochije, “Generator and Magnetic Flux Conducting Unit”, Worldwide PCT GB/2007/0088316 filed 14th March 2007, UK Patent Ref No. 0605298.9 , filed 16th March 2006

Patent 2 (UoE) Mueller & McDonald, “Magnetic Flux Conducting Unit (Hollow Section Core)”, PCT Ref No. GB/2008/003028, filed 8th September 2008, UK Patent Ref No. 0717746.2, filed 12th September 2007

## Book chapters

ALLAN, G. J., GILMARTIN, M., MCGREGOR, P. G., SWALES, J. K. & TURNER, K. (2008), “Lessons from recent computable general equilibrium analyses of energy efficiency improvements: rebound and backfire effects”, chapter in *Energy Efficiency Research Trends*, Bergmann, D.M. (ed), Nova Science Publishers, ISBN 1-60021-880-4.

ALLAN, G., GILMARTIN, M., MCGREGOR, P., SWALES, K. & TURNER, K. (2008), “Modelling the economy-wide rebound effect”, Chapter 4 in “Energy Efficiency and Sustainable Consumption: The Rebound Effect” (eds. Steve Sorrell and Horace Herring), October 2008, Palgrave, ISBN 978-0230525344.

ALLAN, G., GILMARTIN, M., MCGREGOR, P., SWALES, K. & TURNER, K. (2009), “Energy efficiency”, Chapter 7 in “International Handbook on the Economics of Energy”, (ed. J. Evans and L. Hunt), October 2009, Edward Elgar, ISBN 978-1847203526.

## Talks/ Presentation

SAVIDGE, G., BIRKETT, D., INGER, R. & KENNEDY, R.: “The SeaGen tidal turbine: Impacts on Strangford Lough”, *British Ecological Society Annual Meeting 2010*, Leeds, UK.

Selected aspects of environmental monitoring associated with the commissioning and early operational phases of the 1.2 MW SeaGen tidal turbine will be presented. Shore monitoring of seal, porpoise and seabird activity in the vicinity of the turbine has indicated certain significant but spatially very limited changes in activities. Four benthic faunal surveys demonstrate no significant change in the benthic communities associated with the dynamic seabed conditions. The monitoring programme is ongoing.

KREGTING, L., SAVIDGE, G. & BLIGHT, A.: “Influence of water motion on the growth rate of *Laminaria hyperborea*”, *British Phycological Society Annual Meeting 2011*, Cardiff, UK.

Increasing interest in the commercial potential for extracting energy from waves and tidal currents inshore has led to the development of full scale prototype electricity generating devices. For one such wave device, it has been estimated that a commercially viable array may extract approximately half of the wave energy incident arriving on shore. Macroalgal growth is dependent on the movement of the surrounding medium; however the mechanism by which water motion influences the growth rate of macroalgae is multifaceted and includes nutrient transport effects, dynamic stress and suspension of light absorbing sediment. In this study we focus on the influence of the local flows on the seasonal patterns of kelp growth and the associated internal nutrient status of the plants. Measurements were made at monthly intervals from April 2009 of the growth rates of the kelp *Laminaria hyperborea* located at approximate depths of 5 m and 10 m (related to MLW) at each of two closely adjacent sites exhibiting high and low wave energy characteristics. The internal nutrient status (nitrate, ammonium and phosphate) of each population was also determined. Continual monitoring of the wave and current climate and water temperature was carried out at each site using an Acoustic Doppler Current Profiler. Relative light levels were also sampled semi-continuously while samples for the estimation of ambient seawater nutrient concentration were collected concurrently at the time of the plant surveys. The results will be discussed.

KREGTING, L., SAVIDGE, G. & HEPBURN, C.: “Influence of hydrodynamics on growth and nutrient uptake of juvenile *Laminaria digitata*”, *British Phycological Society Annual Meeting 2011*, Cardiff, UK.

Availability of nutrients can be considered one of the most important environmental factors influencing growth rates of macroalgae. However the rate of flux of ions such as those of inorganic nitrogen to a macroalgal thallus surface will depend in part on two factors: (1) the thickness of the diffusion boundary-layer (DBL), which depends on whether water flow is laminar or turbulent and is directly influenced by water velocity, (2) the metabolic demand of a macroalga, which will influence the rate of ion removal from the DBL. If metabolic demand is high, because a macroalga is nutrient deficient, then the rate of removal of an ion from the DBL will increase. However if a macroalga is nutrient replete or some other factor is limiting growth (eg. light) then the rate of ion removal will be lower. Therefore the degree to which water motion will influence nutrient uptake, and therefore growth, will depend in part on the internal nutrient status of macroalgae and the uptake rate of nutrients. The objective of this study was to examine the effect of oscillatory flow (turbulent flow) versus unidirectional flow (constant flow) on growth rates and nitrate uptake by the juvenile kelp, *Laminaria digitata*, in winter and summer when ambient seawater nutrient concentrations are maximal and minimal. Oscillatory flow experiments were conducted at a range of periods ( $T = 3 - 6$  seconds) and average velocity's between 2 and 18  $\text{cm s}^{-1}$ . Unidirectional flow experiments were conducted between 4.5 and 20  $\text{cm s}^{-1}$ . The internal soluble nitrogen pools of *L. digitata* were also measured. Results suggest that increased velocity increased growth rate and nitrate uptake by juveniles in the low nitrogen summer period for both oscillatory and unidirectional flow, but not in winter when nitrogen is found in high concentrations.

### Appendix 3 Alphabetical listing of publications

AGGIDIS, G. A.: “The Lancaster marine energy research in the context of the International Ocean Energy Symposium 2009 in China”, **Invited Paper**, *International Ocean Energy Symposium 2009 (IOES-2009)*, Harbin, China, 17-18 September 2009.

<http://derc.hrbeu.edu.cn/%E6%96%B0%E8%8B%B1%E6%96%87%E4%BC%9A%E8%AE%AE%E9%80%9A%E7%9F%A5.htm> (WS 2.6)

ALEXANDRE, A., STALLARD, T. & STANSBY, P. K.: “Wavefield modifications due to a wave energy converters array”, *Proc. Coastlab 10*, 28th September – 1st October 2010, Barcelona, Spain.

<http://www.coastlab10.com/> (WS 4.14)

ALLAN, G. J., BRYDEN, I., MCGREGOR, P. G., STALLARD, T., SWALES, J. K., TURNER, K. & WALLACE, A. R. (2008), “Concurrent and legacy economic and environmental impacts from establishing a marine energy sector in Scotland”, *Energy Policy*, Vol. 36, No. 7, July 2008, pp. 2734-2753.

<http://www.sciencedirect.com/science/article/pii/S030142150800075X> (WS 9.3)

ALLAN, G. J., McDONALD, J., MCGREGOR, P. G. & SWALES, J. K.: “A distinctive Scottish energy policy?”, *Fraser of Allander Economic Commentary*, June 2008, Vol. 32, No. 1, pp. 46-60.

[http://www.strath.ac.uk/media/departments/economics/fairse/backissues/media\\_144845\\_en.pdf](http://www.strath.ac.uk/media/departments/economics/fairse/backissues/media_144845_en.pdf) (WS 9.1)

ALLAN, G. J., MCGREGOR, P. G., & SWALES, J. K.: “The electricity generation mix in Scotland: The long and windy road?”, with Peter McGregor and Kim Swales, *Fraser Economic Commentary*, Special Issue No. 1 – Energy and pollution, January 2011, pp. 62-72.

[http://www.strath.ac.uk/media/departments/economics/fairse/specialissues/Special\\_Issue\\_No\\_1\\_-\\_Energy\\_&\\_Pollution\\_-\\_Jan\\_2011.pdf](http://www.strath.ac.uk/media/departments/economics/fairse/specialissues/Special_Issue_No_1_-_Energy_&_Pollution_-_Jan_2011.pdf) (WS 9.14)

ALLAN, G., AULT, G., MCGREGOR, P. G. & SWALES, J. K.: “The importance of revenue sharing for the local economic impacts of a renewable energy project: A social accounting matrix approach”, *Strathclyde Discussion Paper in Economics*, No. 08-11, 2008.

<http://www.strath.ac.uk/media/departments/economics/researchdiscussionpapers/2008/08-11strathecon.pdf> (WS 9.9)

ALLAN, G., EROMENKO, I., MCGREGOR, P. & SWALES, K.: “The regional electricity generation mix in Scotland: A portfolio selection approach incorporating marine technologies”, *Energy Policy*, Volume 39, Issue 1, January 2011, Pages 6-22, ISSN 0301-4215, 10.1016/j.enpol.2010.08.028.

<http://www.sciencedirect.com/science/article/pii/S0301421510006439> (WS 9.12)

ALLAN, G., GILMARTIN, M., MCGREGOR, P. & SWALES, K.: “Levelised costs of wave and tidal energy in the UK: Cost competitiveness and the importance of “banded” Renewables Obligation Certificates”, *Energy Policy*, Volume 39, Issue 1, January 2011, Pages 23-39, ISSN 0301-4215, DOI:

10.1016/j.enpol.2010.08.029. <http://www.sciencedirect.com/science/article/pii/S0301421510006440> (WS 9.13)

ASHTON, I., JOHANNING, L. & LINFOOT, B.: “Measurement of the effect of power absorption in the lee of a wave energy converter”, *28th ASME International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2009)*, Honolulu, Hawaii, 31 May - 5 June 2009.

<http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=ASMECP002009043444001021000001&idtype=cvips&gifs=yes> (WS 6.6)

BAILIE, H., & BRYDEN, I.G.: “Influence of a quadratic Power take off on the behaviour of a self contained inertial referenced Wave energy converter”, *Proceedings of the Institution of Mechanical Engineers, 2011, Part M, Journal of Engineering for the Maritime Environment*, in press. <http://pim.sagepub.com/>

(WS 3.29)

BARBOUR, E., & BRYDEN, I.G.: “Energy Storage in Association with Tidal Current Generation Systems”, *Proceedings of the Institution for mechanical engineers, Journal of Power and Energy*, DOI:

10.1177/0957650911399014, 2011. <http://pia.sagepub.com/content/225/4/443.refs> (WS 3.26)

- BASTON, S., & HARRIS, R.: “Modelling the Hydrodynamic Characteristics of Tidal Flow in the Pentland Firth.” *Paper No 317 in Proceedings of the 9<sup>th</sup> European Wave and Tidal Energy Conference*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/> (WS 10.17)
- BEHARIE, R.: “Measurements of shoreline wave action to establish possible environmental and ecological effects from wave energy converter arrays.” *Proceedings of the 9<sup>th</sup> European Wave and Tidal Energy Conference*, 5-9 September; Southampton, UK. 2011 <http://www.ewtec.org/> (WS 10.18)
- BELL, M. C. & SIDE, J.: “Environmental impacts of tidal and wave power developments and key issues for consideration by environment agencies.” *Background Report on Task 2 of Sniffer ER20. Scotland and Northern Ireland Forum For Environmental Research*, Edinburgh, 2011. <http://www.sniffer.org.uk/> (WS 10.12)
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