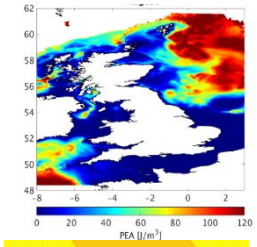
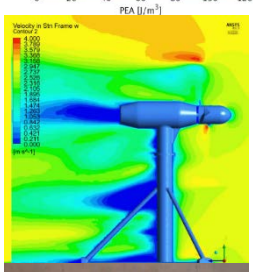
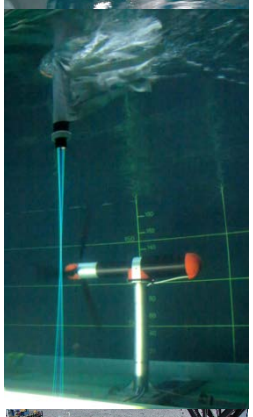
UK CENTRE FOR MARINE ENERGY RESEARCH







SUPERGEN UKCMER

Full Report

November 2016

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Academic and research staff also acknowledge with deep gratitude the interest, assistance and many forms of collaboration received from the following:

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Foreword

The Supergen Marine energy research consortium was established in October 2003. Phases 1 and 2 each lasted four years. Phase 3 began in October 2011 with four core and seven associate universities and lasted five years. Awards from the supporting EPSRC Grand Challenge programme resulted in 25 universities with around 100 academic and research staff working together in the UK Centre for Marine Energy Research (UKCMER). This 2016 full monograph describes the work completed and ongoing at the end of a five year aggregated programme. Phase 1 & 2 monographs were produced in 2007 and 2011. This phase 3 monograph consists of five sections and contains three appendices. Section 2 summarises research in phase 3 over the last five years of the programme. The aims of the future research in Phase 4 are presented in section 3. The Doctoral Training Programme and Dissemination, Engagement and International Articulation activities are summarised in sections 4 and 5. Appendices 1-3 contain details of the individuals involved in the programme, abstracts of the research outputs from phase 3 grouped by theme then alphabetically. All monographs, including this are available from http://www.Supergen-marine.org.uk/references/monographs.

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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 established in 2003 to establish a platform for the development of new and improved devices, processes, facilities and know-how for sustainable power generation and supply and with the aim of increasing coherence and collaboration across the energy research landscape.

1.1 Phases 1 and 2

Supergen Marine Phase 1 (October 2003 – September 2007) brought together research staff from the Universities of Edinburgh, Robert Gordon, Lancaster, Heriot-Watt and Strathclyde. The research aimed to:

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

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.

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. They delivered generic research in 12 work streams (WSs) with the following objectives:

- 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.
- 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.
- Internationalise its articulation, activities, perception and influence.

Twelve research work streams (WSs) were undertaken:

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 their Doctoral Training Programmes, Phases 1&2 trained over 40 PhD students. The outcomes and publications of this work are recorded in the Phases 1 and 2 monographs, copies of which are available at the Supergen Marine website: http://www.Supergen-marine.org.uk/references/monographs.

1.2 Phase 3

Phase 3 commenced in October 2011, funded by EPSRC under award EP/I027912/1 bringing together staff from the core Universities of Edinburgh, Queen's Belfast, Strathclyde and Exeter. The consortium included associate Universities of Plymouth, Heriot-Watt, Lancaster, Manchester, Swansea, Oxford and Southampton. Together they formed the UK Centre for Marine Energy Research aiming to ensure joined-up regional, disciplinary and thematic effort by:

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

The research in phase 3 was grouped into five themes:

- **Arrays and farms** – to understand and better quantify the interactions between devices, the energy flux in the sea, the natural environment and the electricity network - to optimise behaviour and energy yield;
- **Environmental interaction** – to understand the 3D time varying interaction between single and multiple devices and the energy and natural environment arising from the local and large-scale abstraction of energy through electricity generation;
- **Extreme loadings and durability** – to become able to predict the extreme conditions, their consequent device and structural loading and the effects on the ultimate survival of components, technologies or devices;
- **Fatigue loadings and reliability** – to become able to predict the effects of combined wave and tidal action on the cyclic loadings and the effects on the wear-out or fatigue failure of components, technologies or devices;
- **Novel marine energy systems and components** – to develop new wave and tidal energy device concepts, sub-systems and components that improve from those existing.

During phase 3 there were three Grand Challenge calls for proposals to extend the research base and broaden the contributing community. They generated very considerable interest and many excellent proposals, from which the following were selected by peer-review. Phase 3 integrated the staff and activities of these GC projects into the hub in the themes above. All but the most recent of the Grand Challenge Projects are complete and key highlights are reported in section 4 of this monograph.

Optimal Design of Very Large Tidal Stream Farms for Shallow Estuarine Applications; Oct12-Mar16 EP/J010138/1; Prof M Belmont – Exeter, collaborative with Edinburgh.

The Effects of Realistic Tidal Flows on the Performance and Structural Integrity of TSTs; Jul12-Sep15 EP/J010200/1; Prof T O'Doherty – Cardiff, collaborative with Liverpool, Swansea, Bangor and Cranfield.

Extreme Loading of MEDs due to Waves, Currents, Flotsam and Mammal Impact (XMED); Feb12-July15 EP/J010235/1; Prof P Stansby – Manchester, collaborative with Plymouth and Edinburgh.

Modelling Marine Renewable Energy Devices - Designing for Survivability (ELoWEC); Jun12-Dec15 EP/J010197/1; Prof C Swan – Imperial, collaborative with Queens and Manchester Metropolitan.

Supergen Marine Technology Challenge (SMARTY); Oct12-Mar16
EP/J010316/1; Prof P Taylor – Oxford, collaborative with UCL and Bath.

Step Change for WEC through Floating Multi-Body Multi-Mode Systems in Swell (STEPWEC); Jun13-16 EP/K012487/1; Prof P Stansby – Manchester, collaborative with Oxford and Bath.

The hydrodynamics of deformable flexible fabric structures for wave energy conversion; May13-Apr16 EP/K012177/1; Prof D Greaves – Plymouth, collaborative with Southampton.

Increasing the life of Marine Turbines by Design and Innovation; May12-Oct15
EP/J010308/1; Prof R Miller – Cambridge, collaborative with Cranfield.

Interactions of Flow, TSTs, Local Sediment Bed under Combined Waves&Tides (INSTRON); Sep12-Feb16
EP/J010359/1; Prof P Dong, - Dundee, collaborative with Hull, Liverpool and Strathclyde.

LS-Interactive Coupled 3D Modelling for Wave & Tidal Energy Res&Env Impact (Terawatt); Jun12-Nov15
EP/J010170/1; Prof J Side – Heriot-Watt, collaborative with Edinburgh, Strathclyde, Swansea & UHI

EcoWatt 2050; Mar14-Feb17
EP/K012851/1; Prof J Side–Heriot-Watt, collaborative with Edinburgh, Strathclyde, Swansea & Aberdeen.

LS interactive coupled modelling of environmental impacts of marine RE farms (LINC); Oct12-Mar16
EP/J010065/1; Dr B Elsaesser: Queens, collaborative with Imperial College and Cefas.

Reducing the Costs of Marine Renewables via Advanced Structural Materials (ReC-ASM); Jun13-Jun16
EP/K013319/1; Prof M Stack – Strathclyde, collaborative with Newcastle and Southampton.

Dynamic Loadings on Turbines in a Tidal Array (DyLoTTA); Jul16-Jun19
EP/N020782/1; Prof T O'Doherty – Cardiff, collaborative with Strathclyde.

Survivability of Floating Tidal Energy Converters (SURFTEC); Sep16-Aug19
EP/N02057X/1; Prof A Williams – Swansea;

All Electric Drive Train for Marine Energy Converters (EDRIVE-MEC); Apr16-Mar19
EP/N021452/1; Prof M A Mueller – Edinburgh, collaborative with Newcastle, Delft and UdeChile

Response of Tidal Energy Converters to Combined Flow, Waves & Turbulence (FloWTurb); Apr16-19
EP/N021487/1; Dr V Venugopal, collaborative with U Highlands and Islands and Heriot-Watt

During the course of phase 3 several of the early deployments of wave and tidal technologies experienced failure either through their inability to survive extreme loadings, their failure under normal loadings in extreme displacements or their early fatigue failure under repetitive cyclic loadings. Concurrently there was a recognition in the wave sector that a structured innovation strategy, based on the phased development and deployment of smaller units that may later be scaled-up, is a potentially more efficient and reliable way of demonstrating and consolidating learning. Interest in the wave sector moved towards the development of components, subsystems and technologies that will lead to improved performance and the availability of ocean-ready and durable elements and know-how. The ETI:UKERC 2014 roadmap re-prioritised R&D needs from the perspective of the sector and identified the high level areas needing most urgent effort: *Device and System Deployment; Sub-Systems; Design and Optimisation Tool Development and Arrays*. Across these, several fields are common, including: *development of reliability tools and demonstration at array scale; array design and modelling tools; hydraulic systems and power take offs; array electrical systems and interaction analysis*. At a European level, the SI Ocean project identified the following priorities: *novel system concepts; device and sub-component level reliability demonstration; reliability tools; resource analysis tools and array interaction analysis*. Experience gained working with developers, observations of unfolding events in the sector and the agendas of recent investments like the ORE-Catapult affirmed the following need for the work of UKCMER. Additional core funding under award EP/M014738/1 as *Extension of UKCMER Core Research, Industry and International Engagement* or Supergen 3+. It seeks to explore numerically and physically the interaction of tidal turbines and wave energy converters with their energy fluxes, one another, their moorings and the electricity network to better understand the cyclic and irregular forces acting and the structural loadings arising, ultimately to reduce fatigue and increase reliability. Staff had to complete other concurrently funded work and only transferred wholly to these WPs in the course of the last year. A 12-month contract extension now schedules the work for completion by December 2017.

1.3 Phase 4

The existing hub of UKCMER was renewed in phase 4 under award EP/P008682/1 in October 2016, with the structure shown and ambitions described in section 5.

2 Supergen Marine Phase 3

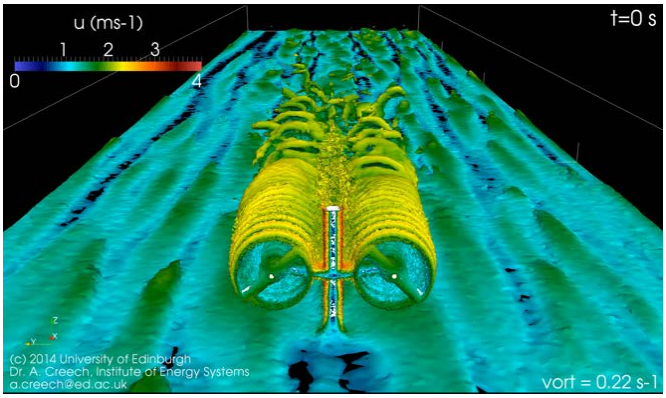
The research in phase 3 was grouped into five themes:

- **Arrays and farms** – to understand and better quantify the interactions between devices, the energy flux in the sea, the natural environment and the electricity network - to optimise behaviour and energy yield;
- **Environmental interaction** – to understand the 3D time varying interaction between single and multiple devices and the energy and natural environment arising from the local and large-scale abstraction of energy through electricity generation;
- **Extreme loadings and durability** – to become able to predict the extreme conditions, their consequent device and structural loading and the effects on the ultimate survival of components, technologies or devices;
- **Fatigue loadings and reliability** – to become able to predict the effects of combined wave and tidal action on the cyclic loadings and the effects on the wear-out or fatigue failure of components, technologies or devices;
- **Novel marine energy systems and components** – to develop new wave and tidal energy device concepts, sub-systems and components that improve from those existing.

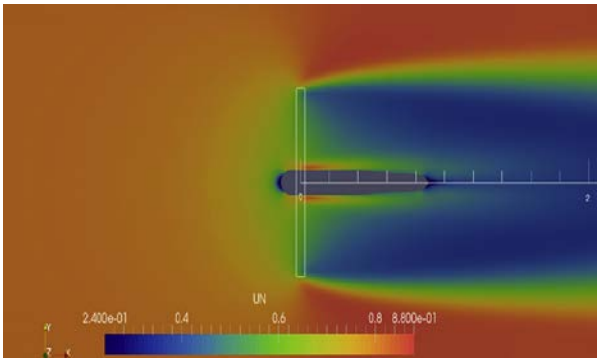
2.1 Arrays and farms

Staff at Edinburgh have developed, for the first time, an accurate, fully-coupled, bi-directional, time-domain, wave-to-wire array model of hydro-dynamically and electrically interacting devices. It can simulate any device form, including nonlinear PTO and mooring forces, in any array shape, driven by multi-directional mixed-spectral seas. It employs state-space analysis to enable accurate prediction of response in time steps short enough to include control system effects and system dynamics, and allows researchers, wave developers and network operators to explore network effects on device behaviour, array geometry and control strategies on power quality. The model has been used to explore the mitigation of power quality issues of connecting arrays of wave energy converters to an electricity network. Inclusion of hydraulic and flywheel energy storage, variable-speed vector-controlled generation and appropriate spacing of WECs within an array, have all been used to smooth the electrical power output and to reduce voltage flicker levels. The model, now with more realistic nonlinear constraints has been used to explore and test global array control strategies which exploit the hydrodynamic interactions between the WECs in an array to show that it is possible to produce more power than with the same number of isolated WECs. With generator speed control included, the control algorithm developed was found to perform as well as global optimal resistive array control with PTO force constraints applied. As part of the Danish SDWED project the model was applied to the WaveStar machine, while for the FP7 PolyWEC project reported in section 2.5 it has been extended to model the use of submerged, flexible, dielectric elastomers as a PTO. Work on wave power absorption and efficiency using cylindrical waves has established a new mathematical reference framework that is more computationally efficient and produced a seminal paper in wave energy. While the power output of a WEC can be accurately determined, the incident power until now could not.

Modelling work in the (consequently-funded) ETI funded PerAWaT project examined the use of actuator disk models using blade element momentum theory to model the turbines. Creech (Edinburgh) has used actuator line models, embedded in the Fluidity flow solver, to model all the turbines in the Lilegrund wind farm off Sweden for Vattenfall, and under (NE/J004227/1 & NE/J004359/1) to simulate a Sea-Gen type turbine in a realistic tidal channel.

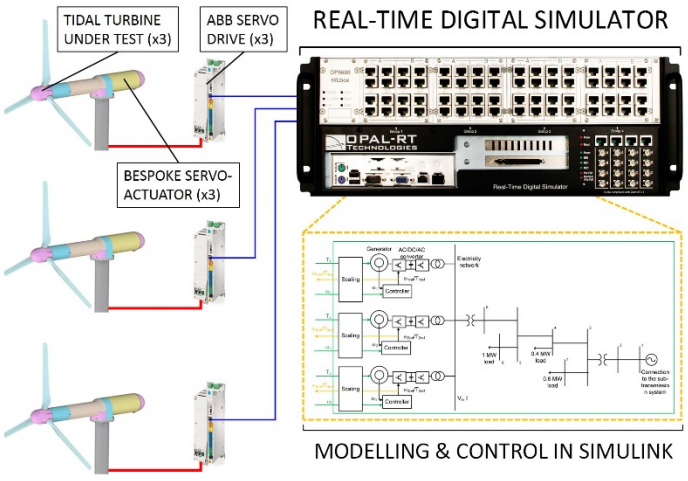


Swansea has developed a BEM-CFD method with an enhanced actuator disk that is able to reduce the computational cost by simulating a time averaged downstream velocity field. The revised BEM-CFD method presented shows a significant improvement over previous BEM-CFD methods when predicting power and thrust. An increase in turbulence intensity in the rotor region, in particular at the wake boundary, improves the recovery of the wake without the addition of empirical turbulence source terms. Good correlation with experimental results for power, thrust and wake prediction has been observed. The model may also be applied to wind turbines. Swansea has developed a RANS computational fluid dynamics model with an embedded blade element actuator disk to study axially aligned turbines, with each in the wake shadow of the previous turbine. The results show uniform effects for a 20 diameters downstream spacing, but more complex interaction for 10 diameters spacing. Investigation of the significance of inclusion of the nacelle and tower geometry in a CFD model has shown that effects are negligible beyond six diameters downstream. Rotational direction has minimal effect on the power generated, but different turbulence is seen in the wake.



Simulations of single, double and triple turbine arrangements have been conducted first to evaluate the effects of turbine spacing and arrangement on flow dynamics and rotor performance. Due to the computational efficiency of this modelling approach, particularly when compared to transient computational fluid dynamics simulations of rotating blades, the BEM-CFD model can simulate larger numbers of devices. An example of how the understanding of the hydrodynamics around devices is affected by rotor spacing can be used to optimise the performance of a 14 turbine array is presented. Compared to a regular staggered configuration, the total array power output was increased by over 10%.

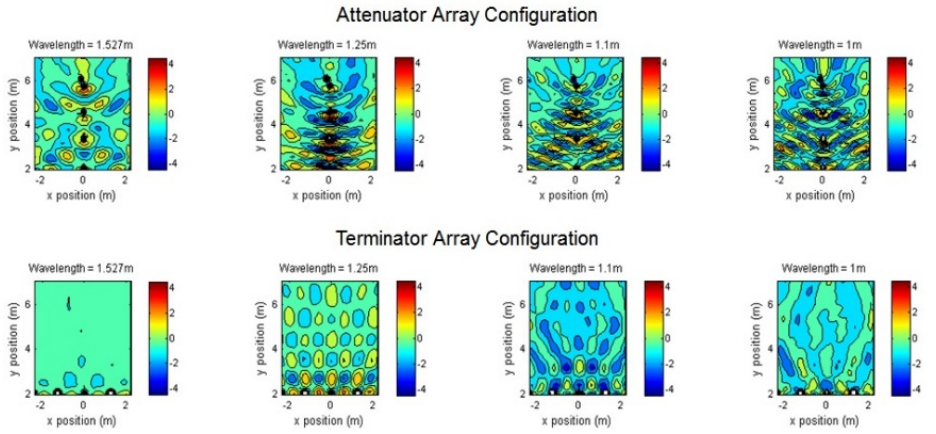
Swansea and Edinburgh are extending an early single machine tide-to-wire numerical model at Edinburgh to become fully-coupled and bi-directional, using the force and angular velocity information from the Swansea current-turbulence-wave transient BEMT to drive an array of tidal turbines. Tightly coupled rotor control algorithms (pitch, stall and over-speed) will allow simulations of small arrays to be performed with both hydrodynamic and electrical connection and control of the turbines, with turbines being affected both by wakes and large scale turbulence in the flow. An extended parametric study of power capping is underway, to develop control strategies for arrays where downstream devices are influenced by the control of upstream devices. Online learning techniques are being developed for the purpose of optimising the torque-speed or power-speed control algorithms used to control the generators in the array.



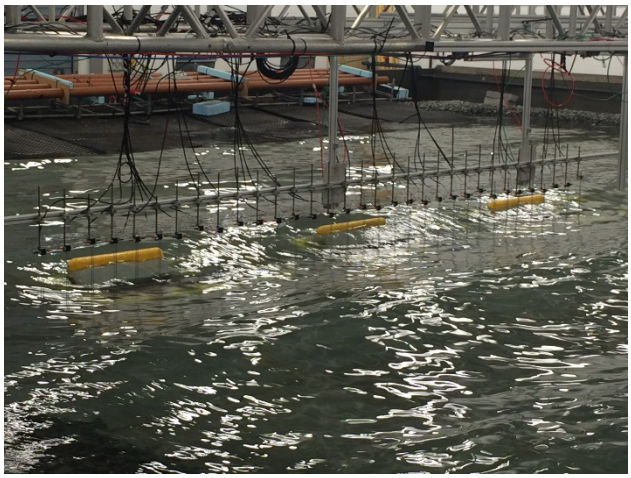
To complement and validate the modelling work, two new fully-controlled scaled tidal turbines are also being built and are nearing commissioning to make up an array of three identical machines. These turbines are

mechanically coupled with permanent magnet servo motors forming a direct drive system. The motors are fully-controllable, through power electronic converters, and can be used in any speed or torque control scheme developed. The turbines will be controlled with a real-time simulator that also acts as an electricity network emulator. Using this hardware set-up, both the effects of different turbine control strategies on the net power generated by the array and the effects of network events on turbine control will be studied. The controllability and flexibility provided by the hardware set-up will also allow the testing of the online learning algorithms developed with the tide-to-wire model. The tide-to-wire model will also be validated using data from experiments conducted with the array of the three scale turbines installed in FloWave.

Work at Queens University Belfast has advanced the theory behind the accurate representation of wave energy converters (WECs) in spectral wave models such as SWAN and Mike21SW. A Kochin function can now be used to represent the waves diffracted and radiated by a wave energy converter. The total Kochin function can be generated by the complex addition of diffraction and radiation Kochin functions, which themselves can be generated from a Boundary Element Method model using a potential flow solver such as Nemoh. It has been found that at any distance greater than about a wavelength the array interaction factors can be derived using a phase-averaged representation of the total Kochin function. This therefore provides an ideal theoretical framework that can be used to represent WECs (together with a spectral-domain model) in spectral wave models. It is expected to be a significant improvement on the current state-of-the-art that uses potential flow theory as it is not only computationally more efficient, but is also able to include variable bathymetry and marine currents within the model. This work was with researchers at L'Ecole Centrale de Nantes, France and the Danish Hydraulics Institute (DHI).



This numerical development of WEC array modelling has been supported by developments in wave tank testing of arrays. In particular high-quality wave-tank testing at Queens has enabled procedures and guidelines to be developed that provided support for future testing of WEC arrays. Tank-testing of individual WECs has also been progressed at Queens with the detailed analysis of non-linear forces on flap-type WECs and how they may be included in numerical models.



Queens has also focused on the design of WECs, and in particular how design principles should vary between different types of WEC. A key finding was that the design of WECs moving principally in heave is very different from those moving principally in surge due to fundamental differences in their hydrodynamic characteristics. The output is designed to move away from the more familiar exposition of a WEC's hydrodynamic coefficients or power performance, and to focus on the underlying physical principles. As a result, a fundamental WEC parameter, "natural bandwidth", has been identified that can be used to assess the significance of phase control to a WEC's performance. Importantly, this parameter can be calculated directly from the

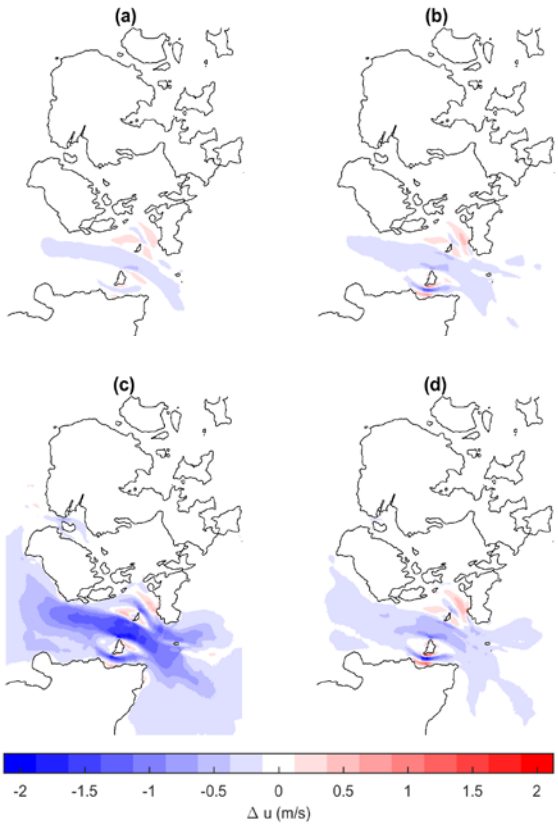
hydrodynamic coefficients and can show which WECs are likely to benefit significantly from phase control (heaving WECs) and those where phase control will have a relatively small impact (surging WECs).

2.2 Environmental interaction

The overall aim of the *Large Scale Interactive Coupled Modelling Of Environmental Impacts Of Marine Renewable Energy Farms* (LINC) project was to demonstrate the ability to numerically model the change in ambient hydrodynamics resulting from the installation of wave and tidal device arrays and to couple the model output to associated ecological models to allow prediction of associated changes in benthic habitats and dynamics, plankton growth and fish communities. The software employed a combination of hydrodynamic and ecological models including: MIKE developed by DHI, Fluidity-ICOM, GOTM and ERSEM.

Some key scientific advances arising from the work include a turbine correction parameter to the enhanced bottom drag formulation that consistently applies a force that remains close to the theoretical value for all grid sizes down to the turbine scale using a simple modification of the drag coefficient. Optimising the design of tidal stream turbines that specifies the number of turbines per unit area and an associated continuous locally-enhanced bottom friction field. The advantages are that outputs of the optimisation are the optimal number of turbines, their location within the farm, the overall farm profit, the farm's power extraction, and the installation cost. A new framework for applying anisotropic angular adaptivity in spectral wave modelling has also been developed with the use of Haar wavelets. This work allows a reduction of computational effort in spectral wave modelling, through a reduction in the degrees of freedom required for a given accuracy, with an automated procedure and minimal cost.

The environmental impact of tidal energy extraction at large (>100 km) and medium (<100 km) spatial scales was investigated using 2D and 3D hydrodynamic-biogeochemistry models. Several large scale tidal energy array scenarios were employed with undetectable effects on the biogeochemistry observed. It was shown that natural variation in the environment such as sunlight had a larger effect on factors such as plankton than changes in hydrodynamics. Current speed together with bottom substrate type was investigated to assess the interaction of these factors in controlling benthic dynamics in high energy environments. Over almost a 1 m/s velocity range investigated, no changes in benthic communities were observed suggesting that the removal of energy by marine tidal energy arrays is unlikely to have a significant effect on benthic communities in high flow environments.

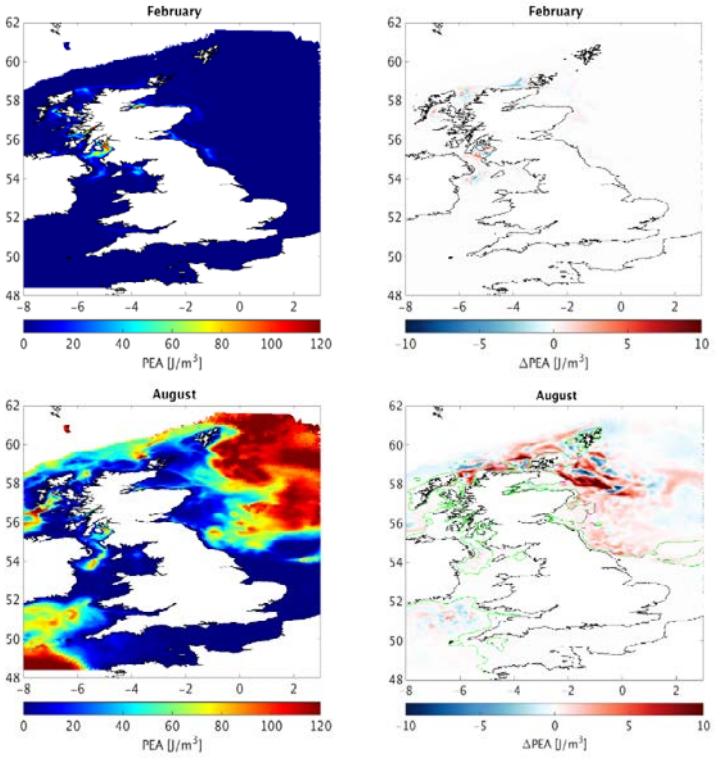


EcoWatt2050 was developed from the earlier Heriot-Watt led project *TeraWatt* which had examined the environmental implications of realistic array developments on sediment, coastal and biological processes using the anticipated Crown Estate Round One license developments as probable future development scenarios. The methodologies and modelling developed for modelling in Delft3D and MIKE3 have been extended by the development and addition of code to the FVCOM software to enable simulation of energy extraction. Model runs have been successfully applied to very large scale arrays across the Pentland Firth, as shown opposite, and the environmental impacts of energy extraction contrasted with those

anticipated from climate change. The work has investigated changes in tidal flow from the placement of tidal turbine arrays extracting (a) 1.39GW (b) 1.40GW (c) 4.9GW and (d) 1.6GW, for different array configurations.

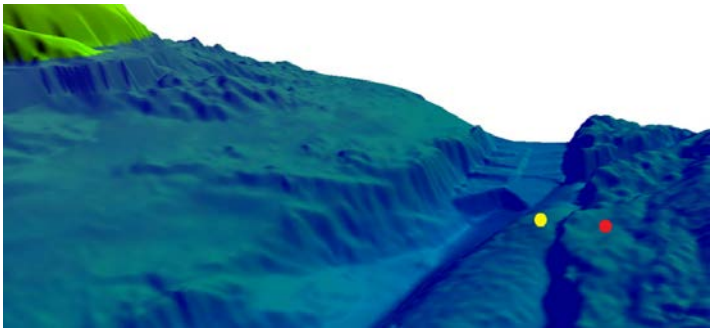
New approaches to the prediction of sediment grain size have been developed with maps of annual mean and maximum depth-averaged tidal velocity and wave-orbital velocity at the seabed for the UKCS.

A number of approaches to the elaboration of environmental impacts have also emerged. The illustration below shows changes to the Potential Energy Anomaly (PEA) from very large scale tidal array deployment in the Pentland Firth in February and August. The LHS shows baseline PEA (the amount of work required to bring about complete vertical mixing of the water column and the RHS the changes as a consequence of 2,800 tidal turbines (ca. 1.6GW) in arrays across the Firth. This provides an indicative measure of changes to stratification of the water column and hence availability of nutrients and consequent primary production.



TeraWatt research identified the challenge of spatially distributing values for bed resistance within modelling approaches, and the data gaps necessary for the calibration and validation of numerical models were to be attempted. The ongoing GC project FlowTurb is designed to address turbulent structures within complex combinations of tidal flow, waves and turbulence.

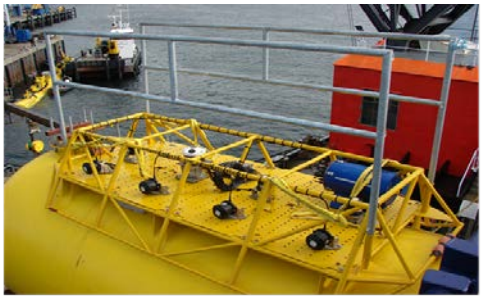
Swansea has investigated numerical modelling of micrositing variability and mean flow scaling of marine turbulence in Ramsey Sound and compared the results with two acoustic Doppler current profiler measurement campaigns carried out in the Sound at two locations within 50m of one another. This enabled the characterisation of turbulence through turbulent kinetic energy (TKE) density and integral lengthscales and related them to one another and with mean flow parameters. The expected quadratic scaling was not well supported by the data at either measurement location suggesting that more energetic turbulent flow may instead appear to be less turbulent if judged by turbulence intensity. The correlation between lengthscales and TKE density is highly site-specific and it should not be assumed that highly energetic turbulence is associated with larger flow structures or vice versa.

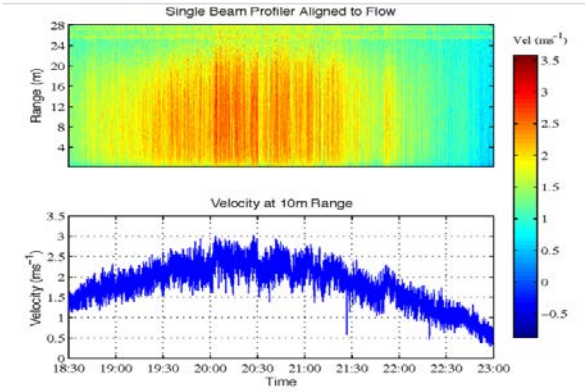


Work at Swansea has identified a means of predicting the effects of the presence of tidal turbines on the local physical environment that could affect fish. Computational prediction of pressure change in the vicinity of tidal stream turbines and the consequences for fish survival rate considers the effects of sudden changes in pressure and turbulence along a streamtrace. A new Individual Based Model (IBM) framework has been developed to mimic the habitat usage of marine mammals in energetic tidal sites. In particular, the model has been developed with the aim of investigating the potential impacts of tidal turbines on harbour porpoises in coastal areas. The model makes use of existing tidal/coastal models to define a

simulation environment within which boids (objects representing the animals being simulated) can be released and their behaviour and motion tracked. This data has been taken from results of simulations carried out using the TELEMAC shallow water model, with the addition of data representing food availability and additional noise levels. The work shows small but detectable changes in habitat use by the simulated porpoise resulting from the addition of a noise source representing the turbine.

An array of single beam Doppler current profilers for high resolution measurement of three-dimensional tidal flow velocities has been developed by Edinburgh and subsequently tested at the EMEC tidal site. The instrumentation gives a higher spatial resolution for velocity measurements compared to conventional acoustic Doppler profilers (ADPs). Focussing these acoustic beams creates a sample volume at the focal point of 0.03 m^3. Away from the focal point, the array is also able to simultaneously reconstruct three-dimensional velocity components in a profile throughout the water column. The array has been tested on the operational commercial-scale Alstom 1MW DeepGen-IV Tidal Turbine deployed in the Falls of Warness and compared to traditional ADCP measurements where the beams diverge. Comparisons demonstrate an order of magnitude reduction in realisable length scale compared to traditional ADCPs, a peak cross-correlation coefficient of 0.96 over a 4 second averaging period and a 47% reduction in Doppler noise. Collected data has been packaged for public release and the success of the technology has led to similar deployments at the FAST site in Canada.



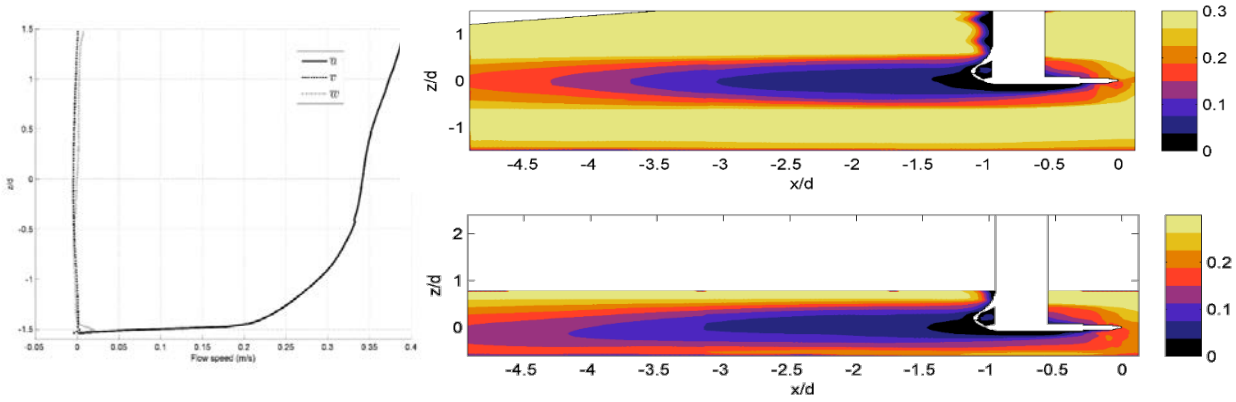


Work at Exeter in *Optimal Design of Very Large Tidal Stream Farms for Shallow Estuarine Applications* has developed a new hybrid optimisation approach that allows the multi-objective optimal design of the layout and power loadings of large tidal energy arrays operating in shallow medium flow (2m.s^{-1}) estuaries but the technique can be applied to all types of marine energy farms. Optimisation is subject to minimising flood risk, with further environmental impacts, such as sediment transport driven outcomes, being capable of subsequent incorporation as slow timescale effects. It has shown that large farm induced phase shifting effects on estuarine resonance can be typically neglected. This means that flood risk and habitat impact (associated with moving peak flow closer to peak depth) caused by introducing such farms is modest. A general trend has been found confirming that staggered deployment of turbines rather than rows in a stream-wise direction tends to be preferred. For the horizontally deployed high aspect ratio turbines, that were the basis of the project, detailed CFD showed that the lateral interactions were very weak even at high blockage ratios and that stream-wise interactions are inevitably strongly non-linear. A test campaign in the FloWave tank supported the numerical modelling.

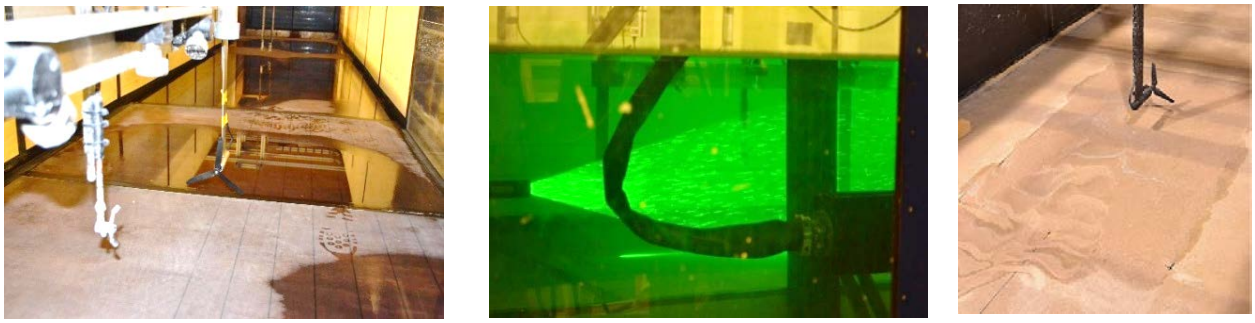
The *Interactions of Flow, TSTs & Local Sediment Bed under Combined Waves & Tidal Conditions (INSTRON) project at Dundee* investigated the fundamental processes controlling the complex flow-tidal turbine-sediment interactions and sought to improve prediction methods in site design and planning.

A new 3D CFD flow model has been developed based on the FLUENT package. The tidal turbine is represented through the virtual blade method. The dynamics of the free surface are simulated through

the VoF method. A new 3D LES-ALM flow model has been developed and tested against the data obtained in experiments at Liverpool and by Hull within this project.



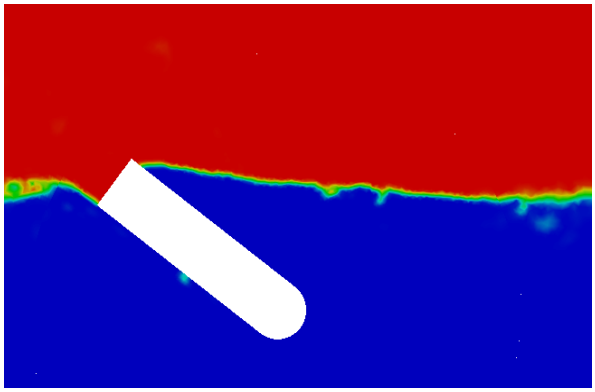
Experiments with a rotor in a flume with a mobile bed were carried out to reveal that the design of the rotor blade has a significant impact on the generation of vortex-shedding from the rotor tips and increased asymmetry of the wake observed as the rotors are lowered through the boundary layer. Increased turbulence kinetic energy around 2.5 rotor diameters downstream of the blades was found to be similar to patterns of scour observed in the bed. It was also found that the rotor eroded the bed in the near wake region (about 5 rotor diameters) and also caused a significant decrease in the flow as far as 15 rotor diameters. The experiments show that the sediment bed may have an effect on the efficiency of tidal turbines and should be taken into account in the installation and design of marine turbine farms.

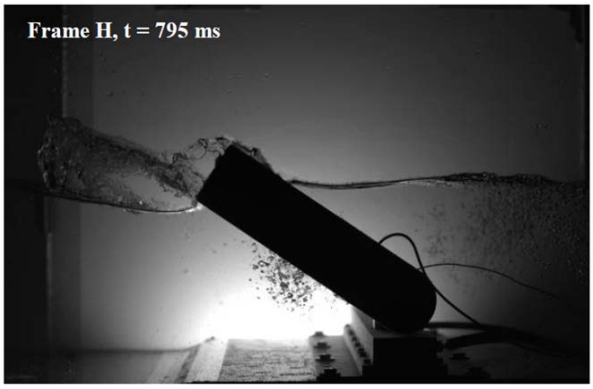


2.3 Extreme loadings and durability

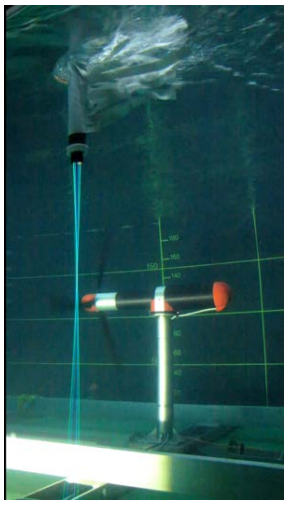
Work at Imperial College on the *Extreme Loading of Wave Energy Converters (ELoWEC)* project considered the interplay of nonlinear load amplifications and viscous dissipation on heaving buoy type devices. Nonlinear load amplifications are generally associated with larger-than-expected device motions, and are also important if mooring survival is of concern. In contrast, viscous dissipation commonly leads to motion reductions. Using more than 150,000 individual laboratory wave events, load amplifications of up to 60% were identified in the steepest sea states compared to industry standard codes. However, despite these load amplifications, device motions were significantly smaller than commonly predicted. The reason for this lies in the fact that viscous damping dominates the overall response around resonance. Whilst this type of response is known, the work quantified for the first time, the interplay between viscous damping and nonlinear forcing. In considering the extreme loading of surface piercing Oscillating Wave Surge Converters (OWSCs), a new OWSC physical model, capable of accurately measuring both local and global loads, was developed. This model was used to investigate the extreme loading mechanisms experienced by large, surface piercing OWSCs. It was found that slamming is the primary impulsive extreme loading mechanism. A novel experimental technique was developed to provide a more appropriate means of testing beyond the current confines of industry standard practice. The technique combines the use of a bespoke short duration wave packet coupled with a probabilistic occurrence analysis.

This approach is capable of determining the range of extreme loads likely to be experienced, along with their likelihood of occurrence in any sea state. The technique is beneficial in that it significantly reduces physical or numerical testing time, and also reduces load uncertainties. The dynamic and kinematic characteristics of slam loading on a large surface piercing OWSC were identified.





This, in turn, led to the identification of primary and secondary governing variables, which were used to describe extreme loading mechanisms. The accompanying numerical study of an OWSC device established another key finding of the work. The numerical model developed demonstrated that to predict the peak slamming pressure correctly, a multi-phase compressible code such as the compressible InterDyMFoam should be employed.



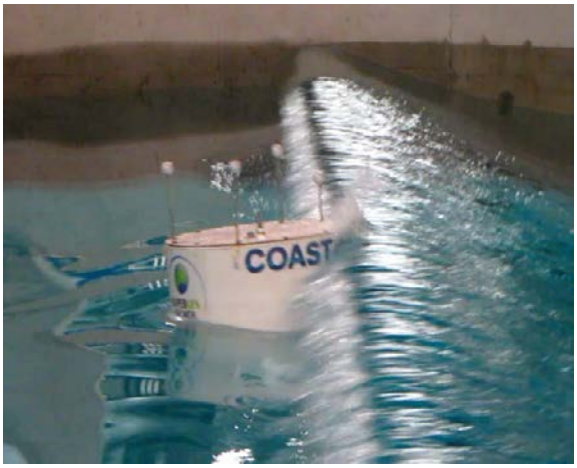
The *Extreme Loading of MEDs due to Waves, Currents, Flotsam and Mammal Impact (XMED)* project at Manchester identified improved understanding of extreme loading on tidal turbines and wave energy devices, through the development of modelling approaches accounting for combined waves and currents, and impacts due to flotsam and marine mammals. Massively parallel CFD was further developed for simulation of unsteady loads. Part of this phase of work was conducted in parallel with the ETI funded ReDAPT project enabling evaluation of load predictions against loading measurements from the full-scale Alstom/GE turbine deployed at EMEC. CFD in the form of computationally intensive LES with tidal turbulence represented (Synthetic Eddy Modelling) has successfully predicted blade load spectra. Frequency ranges over which blade loads are affected by onset flow shear, onset flow turbulence and blade-generated turbulence have been identified, including wave effects. Laboratory studies at about 1:70 scale were undertaken using a single rotor in turbulent flow and waves, a porous disc representation in the same conditions and arrays of rotors (up to 12). A bed mounted turbine of 1.2 m diameter was also designed with custom instrumentation for measurement of loading and wake due to turbulent flow and waves in water depths of around 2 m. The system was commissioned and preliminary analysis conducted at IFREMER with subsequent tests in FloWave. The unit has since been modified for use in *FloWTurb*.

Turbine and turbine array modelling was undertaken at various levels: BEMT, actuator disc CFD, actuator line CFD, blade-resolved RANS CFD, blade-resolved LES CFD, and wake modelling using far wake self-similarity. The other methods do not pick up the tidal turbulence effects on unsteady loading. The outcomes include fundamental characterisation of near wake and far wake with self-similar formula, formulation for turbulence loading on a turbine, formulation for and predictions of additional wave loading on turbines, up to the maximum wave height for operation and prediction to quantified accuracy of turbine performance and loading in arrays. A fast method for array configuration optimisation was developed to maximise power capture

based on superimposed self-similar far wakes. Fully resolved turbulent channel flows were undertaken using LES at different Reynolds number to define all complex characteristics indicating characteristics change little at sufficiently high Reynolds numbers.

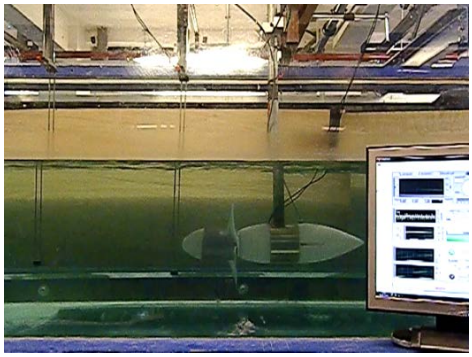
A Smooth Particle Hydrodynamics Lattice Spring Method – has been developed for the purpose of modelling impact between immersed elastic bodies. LSM has been validated for analytic cases of beam deflection and sphere compression. Rotating turbine (based on the generic turbine used in ETI PerAWaT project) has been modelled. The motion of a deformable body within a flow and responding to impact with a rigid body can now be modelled. This has been applied to the (extremely complex) geometry of a whale skeleton (from LiDAR scan) enclosed in material representing blubber with skin impacting on a turbine undergoing forced rotation. An experimental approach has been developed to represent blade tip loads due to impact with a target with material properties representing a marine vertebrate.

Experiments by Plymouth investigated focused wave groups to represent extreme waves, both non breaking and breaking. Snatch loading occurs in both cases and magnitude was found not to be strongly dependent on wave steepness, while float response is. Wave breaking location has a much greater effect than wave steepness on the mooring load. Focused wave groups are considered inadequate to assess fully the extreme loads experienced by a taut moored WEC due to the demonstrated dependence of mooring load on the body's motion and displacement history. The snatch loading was modelled accurately in non-breaking waves using ISPH for Froude Krylov forces and uniform potential flow assumption for added mass. In breaking waves the same approach, however, overestimated by about 30%. This model approach is highly efficient as the same wave can be used for many mooring configurations. In related research slam loading on structures was modelled using two-phase SPH giving good experimental predictions but showing importance of air 'cushioning' is some cases.



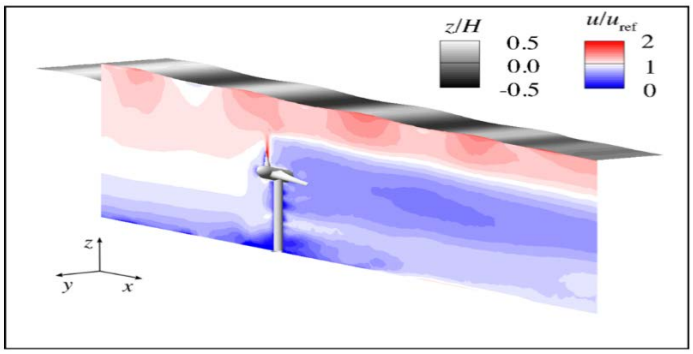
In the *Supergen Marine Technology Challenge (SMARTY)* project Oxford concentrated on prediction of long-term wave power potential and pitch control of tidal current turbines. UCL investigated numerically and through modelling the effects of waves on sheared currents. Bath explored the effects of steep waves on surface piercing columns. Oxford analysed the long-term inter-annual variability of waves at points around the UK coast in the open Atlantic and northern North Sea, and the consequences of this for wave power as a renewable energy resource and machine survivability. Reconstruction of the wave climate is taken back over 300 years to obtain a long time perspective. There is strong coupling between all the wave statistics and the well-known North Atlantic Oscillation and other atmospheric patterns. Although the annual wave climate is extremely variable, less variability survives through into the extracted power once machine characteristics are incorporated, because machines will be sized for the shorter mean wave periods rather than the longer periods for extremes. They then considered the survivability of the Manchester M4 device and showed that, for extreme waves, with long periods, the internal bending motion of the machine is controlled by wave slope and not wave amplitude, providing a limit on motion.

Work at Oxford has developed a means of Individual blade Pitch Control (IPC) for tidal turbines to alleviate unsteady loading (which can lead to fatigue failure), in the presence of strongly sheared mean flow, intense turbulence and flow oscillations due to waves. Computationally, this has required the generation of nested rotating meshes within the OpenFOAM CFD solver. The outer domain is fixed, and represents the flow away from the turbine, then a coin mesh is embedded and rotates with the turbine, finally sub-meshes within the coin may each individually rotate about their own axes to simulate dynamic individual blade pitch as the blade rotates through the azimuth. This new and



unique nested sliding mesh CFD model has been used to study the three-dimensional loading, and flow separation features of rotating blades in adverse flow conditions, which has revealed flow and load differences to engineering model load prediction with and without individual pitch control.

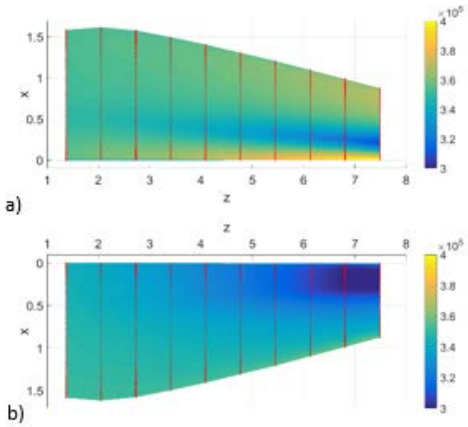
UCL have performed unique experiments in a wave channel for waves on sheared currents, documenting the evolution of the free-surface in the vicinity of the focus point for a large wave group and the internal wave kinematics. Strongly sheared profiles have been generated and shown both to persist down the channel and to significantly affect wave kinematics beyond simple vector addition of waves and current. A novel computational method has been devised for the 2D simulation of waves and sheared current.



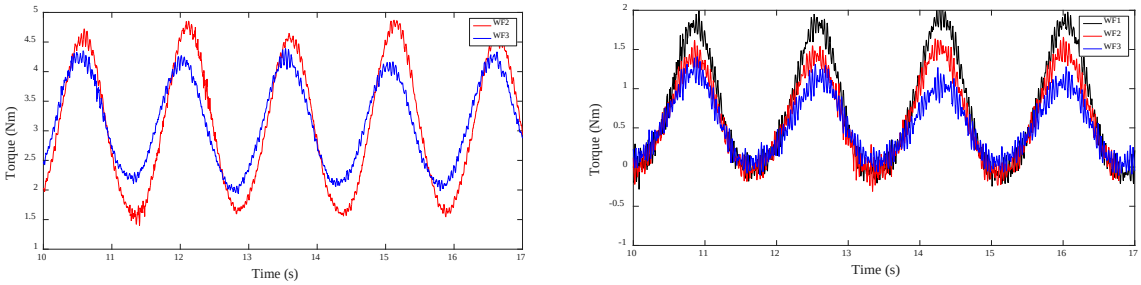
The work at Bath explored the application of OpenFOAM and diffraction calculations to estimate loads on surface piercing columns in steep waves, as might be applied to support structures for marine renewable energy devices generally, as well as offshore wind turbines. Wave impacts on a fixed truncated cylinder under a range of wave conditions (from up to breaking) were tested in two wave basins in Norway and South Korea, and numerical simulations were made by all the groups. The Bath team has produced both OpenFOAM and 2nd order diffraction calculations whose results were compared to experimental data obtained by several of the project investigators in previous work in a Hydralab program at DHI. The CFD allowed much of the harmonic structure of the loads to be resolved using a methodology proposed by FitzGerald, Taylor et al. The results are important for high frequency 'ringing' loads on structural elements close to the free-surface, and have been reported in Ocean Engineering. An iterative correction method developed at UCL has allowed more accurate wave focusing and predictions from the model compare well to the experimental data collected at UCL.

2.4 Fatigue loadings and reliability

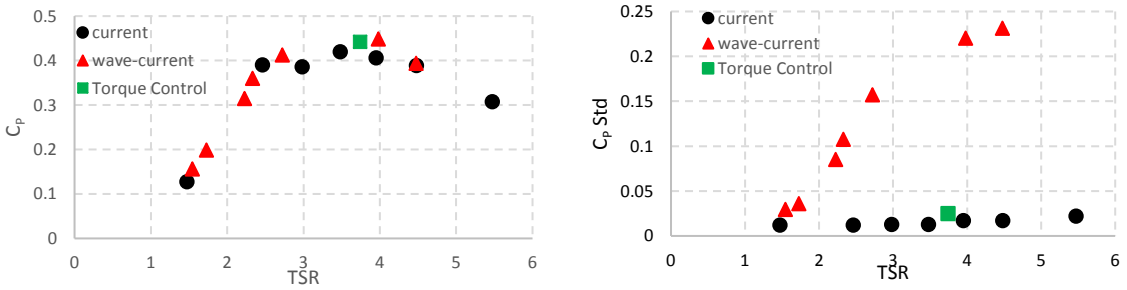
Core research at Strathclyde has developed means to predict and measure tidal turbine performance when operating in combined wave-current conditions with unsteady flows. Early research developed an analytical unsteady BEMT model which integrated wave-current interaction within tidal currents to create unsteady flows representative of the tidal environment, then superimposed this on to the rotors of a tidal turbine and evaluated the impact of the interaction on the power capture characteristics of the rotors. The combined BEMT-2D CFD model has been developed to quantify the resulting pressure distribution to be experienced over a blade surface at reduced computational cost compared to 3D CFD as shown. Comparison with 3D CFD and BEMT models for three different blade geometries and at two different scales demonstrated good model performance. The output data from this informs input parameters to FEA modelling developed for composite blades at laboratory and field scale using BEMT-2D CFD model outputs. This model has been verified using an instrumented 1 m carbon fibre tidal turbine blade undergoing controlled structural and load testing.



A computational model has been developed to estimate fatigue life of tidal turbine blades operating in realistic sea conditions using an unsteady BEMT model (random waves and current) and the occurrence levels of a range of sea states from real tidal site data. This method uses Rainflow analysis with Miner's rule for damage estimates coupled with experimentally obtained S-N curves for composite materials to give quantification to fatigue life of blades.

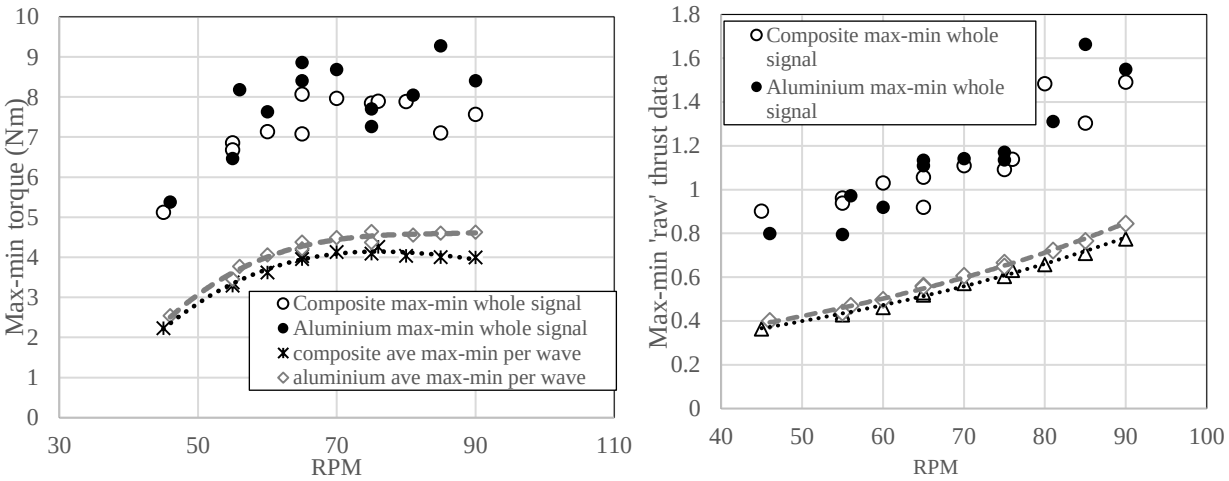


More recent research involved physical testing of a scale horizontal axis tidal turbine in the INSEAN tow tank with and without waves. Wave heights of 0.2 to 0.4m with a 2s wave period in a stationary reference frame were used in combination with tow speeds of 0.5 and 1m/s. These wave conditions were considered to be extreme cases for the scale of testing being undertaken, when using a turbine with a rotor diameter of just over 0.5m. The results obtained demonstrated that the average power coefficients (left) of cases with and without waves were similar; however, standard deviations (right) were larger than those seen in the existing literature due to the extreme wave events.



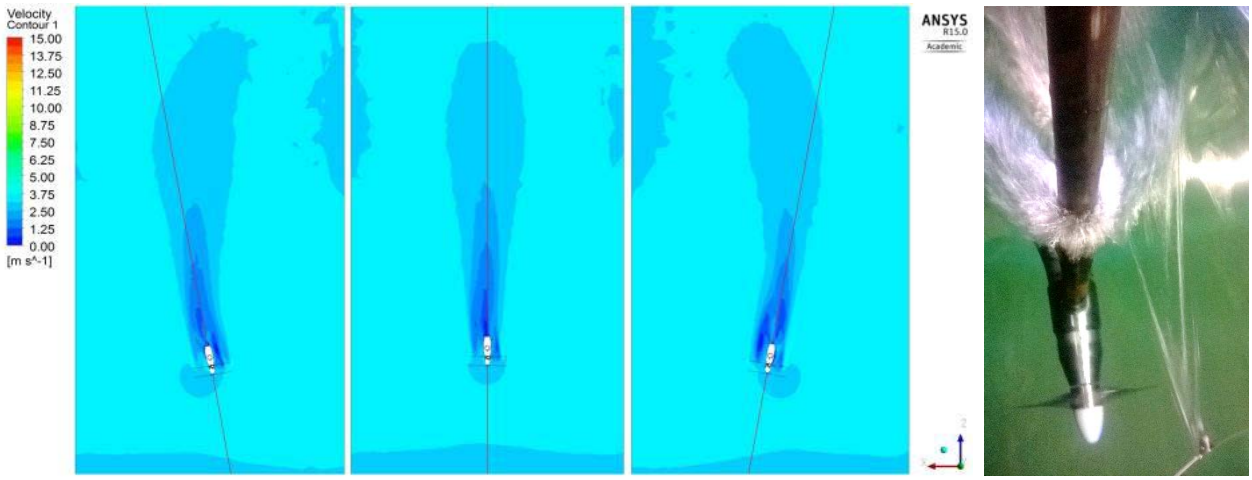
The figures above show the results using a tow speed of 1m/s, without • and Δ with superimposed waves. Initial investigations using torque control demonstrated that the variation of torque is reduced substantially. This is denoted as □ above. The variation in torque was found to decrease by up to almost 50% as the wave height dropped for a given carriage speed and TSR. However, doubling the carriage speed from 0.5 to 1m/s increased the torque range by about 70% for the same wave characteristics, as shown below. The information and data collected from these tests enabled verification of the unsteady BEMT model, giving confidence in the application of the model when using this for assessing full scale applications within real sea conditions.

Building on research investigating bend-twist coupling of composite blades to regulate power delivery, preliminary investigations and testing were undertaken to evaluate the ability of the elastic nature of composite rotor blades to absorb and regulate the transient nature of the power surges delivered by tidal turbines in unsteady flow conditions. A testing program was undertaken on a scale tidal turbine at the circulating tank at IFREMER using 0.2m wave heights and 2s wave period at approximately 0.8m/s. Testing was conducted on a three bladed rotor of just under 0.8m diameter and using blades with an NREL S814

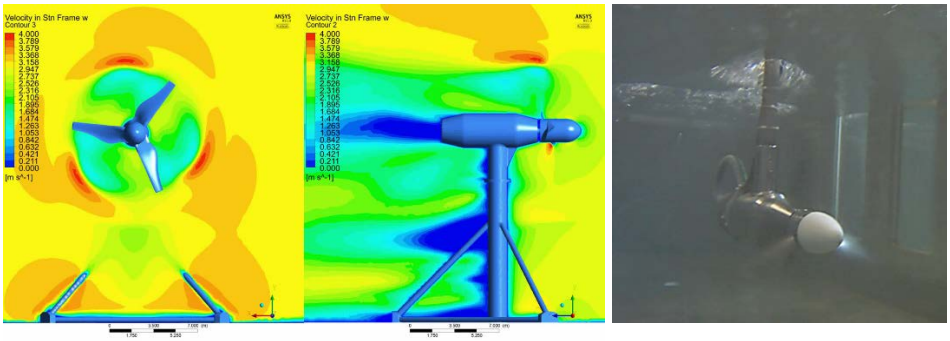


profile. Testing was initially undertaken on the rotor fitted with rigid alloy blades, then repeated for the same unsteady flow conditions for an identical rotor fitted with composite bend-twist coupled. The tests showed that the cases with and without waves presented similar power coefficients for both sets of blades, but that the rotor with bend-twist composite blades developed slightly lower torque and thrust fluctuations than that associated with the rigid alloy blades. This initial evaluation suggests the elastic nature of the bend-twist coupled composite blade set can dampen and provide some form of passive regulation to power delivery from tidal turbines operating in transient unsteady flow conditions.

In the Cardiff project *The Effects of Realistic Tidal Flows on the Performance and Structural Integrity of TSTs* they collaborated with Swansea, Cranfield, Bangor & Liverpool to characterise the performance of a generic tidal turbine under realistic operating conditions of depth-varying and fluctuating velocity profile, arising from the combination of tidal current and depth penetrating severe wave motions. They investigated the impact of these realistic conditions on turbine reliability, maintainability and survivability, with special attention to potential stress cycling and fatigue issues and provided design and analysis tools to support the decision making process undertaken when considering the placement of turbines.



Oceanography data was obtained from sites off the Welsh coast showing that the flow direction fluctuates by $\pm 20^{\circ}$ to the main flow. Based on this improved understanding of conditions including the vertical structure of velocity profile, the role of tidal asymmetry, wave-current interaction, and long-term variability of wave conditions, numerical models of yawed turbines were produced incorporating wave-current models, with and without profiled velocity profiles. Simulations indicated that the power reduces with increasing misalignment along with the thrust, but the shaft bending moments increase substantially. Surface waves and profiled flow exaggerated this effect. Improved understanding of the resulting fluctuating loading on the turbine drive shaft due to wave-current interaction and also due to shadowing of a support structure suggest that the turbine rotor should also be positioned at least two stanchion diameters upstream.

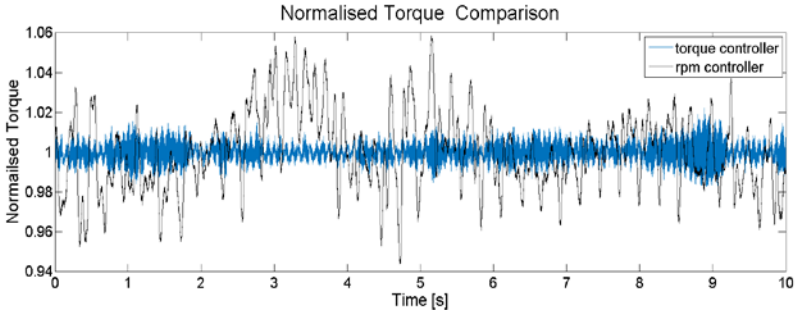


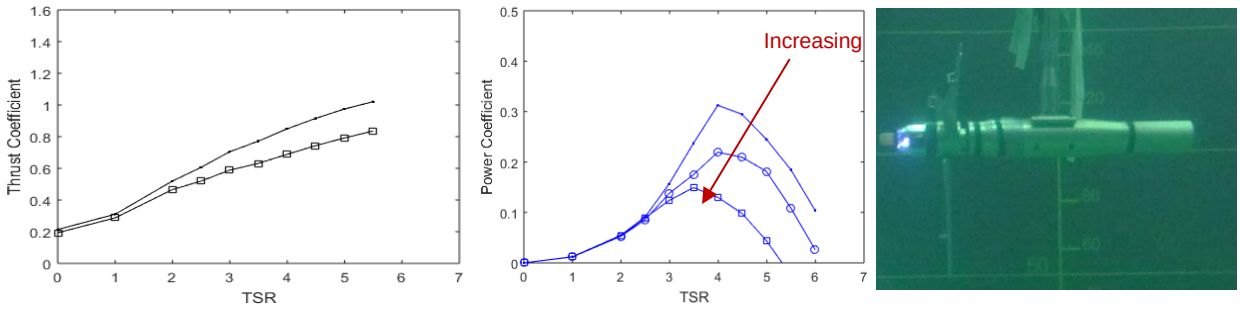
Swansea has extended its blade element momentum model to include synthetic turbulence and investigate tidal turbine gearbox fatigue (in collaboration with Cranfield) and condition monitoring for offset blades (in collaboration with Cardiff). Cardiff developed an instrumented laboratory scale turbine including sensors and data acquisition for measuring blade root loads, torque, power and 3 axis vibrations. A data transfer rate of 250 Hz ensured the provision of high quality data.

Liverpool collaborated in the measurement campaign that took place in their recirculating flow tank. Cranfield developed a monitoring system for tidal turbine gearboxes that can identify faults at the earliest stages of mechanical degradation and a new condition indicator for bearing health assessment. Least Mean Square (LMS) and Fast Block Least Mean Square (FBLMS) algorithms were developed and validated to predict the health of parallel shaft and planetary gearboxes. In addition this research developed a new condition indicator for bearing health assessment. This indicator called impulse energy (IE) indicator can be estimated by separating the bearing signal using signal separation. These have been integrated with Cardiff's work to develop a turbine failure model and identify the needs of an appropriate condition monitoring system and best monitoring strategies for failure prognosis. These have been used within the Cardiff Drive Train test bed to mimic the effects of sea conditions to produce inputs into a drive train. Validation was performed by comparing turbine load and speed data generated numerically using flow data from a tidal turbine site with experimental data from the laboratory scale turbine. The response of the generator to inputs has been integrated into a novel condition monitoring approach. This rig can enact input characteristics associated with extreme sea conditions that cannot be otherwise replicated and directly measure the response of the drive train and power generation.

Cardiff's scale turbine measuring operational blade root loads, torque, power and 3 axis vibrations has been tested in Liverpool University's recirculating flume and in both the Strathclyde University and INSEAN (Rome) tow tanks. The testing has produced a calibrated turbine that can be deployed with known fault conditions and is capable of supporting the verification of these prognostic models. In particular blade force measurement and variable blade angle settings can be used in future prognostic tool proving.

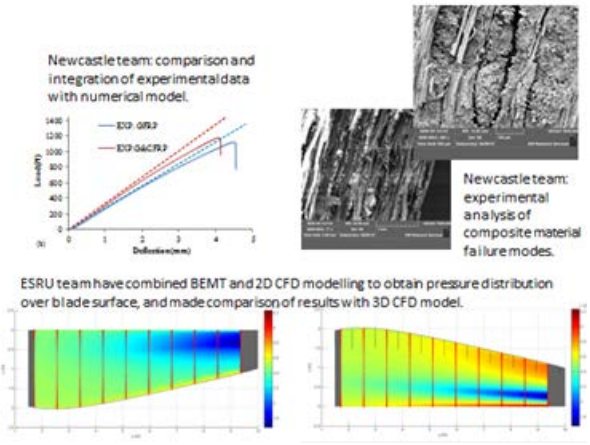
Work at Cambridge on *Increasing the life of Marine Turbines by Design and Innovation* aimed to reduce the unsteady loading on tidal turbines and support structures by decoupling unsteady flow and thrusts/torques generated. Their work quickly established that ADCPs have fundamental limitations and a novel turbulence probe has been built and tested at IFREMER where it gave good agreement with a high-fidelity LDV measurement system. A novel inflow generator for LES has been developed within the OpenFOAM framework. This new technique can reproduce structures in the flow with high accuracy, which is vital for assessing the effect of transient loads on the fatigue life of a tidal turbine. This new code is an enabling tool for LES calculations on highly anisotropic, inhomogeneous turbulent flows in tidal channels. A Blade Element Actuator Line model for OpenFOAM has also been used to verify the impact of different inflows on the turbine fatigue life. Additionally, work on load alleviation studies and transmission tests culminated in 3 weeks of testing at IFREMER showing constant torque/speed/thrust operation with a controller (Cranfield) and load alleviation with three different blade mechanisms (Cambridge). These test have been supported by further wind tunnel testing into optimising the design of the load shedding devices and a back-to-back motor-generator control rig at Cranfield for drivetrain simulations. A time history of normalised torque for speed and torque control is shown, illustrating the significant reduction in the magnitude of torque fluctuations that are obtained through the use of an appropriate control scheme. From the load shedding tests, it was found that torque and thrust can both be held constant using devices on the blade but that they must be controlled separately due to the differing influences of lift and drag. Based on the load shedding results Cambridge has developed a nacelle-mounted microcontroller for a tidal turbine with underwater wifi communication, as a valuable asset for tests where live control from the water surface is required and also for measurement in the rotating frame.



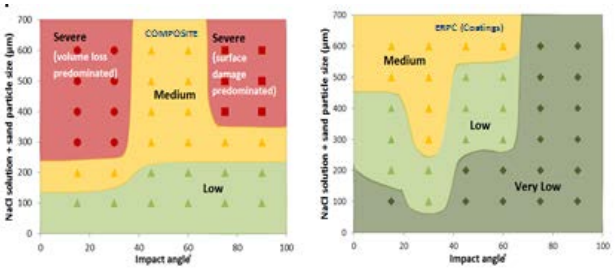


a: Thrust Manipulation (device I) b: Torque Manipulation (device III).

Strathclyde led the *Reducing the Costs of Marine Renewables via Advanced Structural Materials (ReC-ASM)* project collaborating with Newcastle and Southampton. They integrated their hydrodynamic loading model (BEMT) with a structural model (FEM). A novel methodology was developed to obtain high resolution distributed hydrodynamic loads across the blade surface using a combined coupled BEMT-2D-CFD model that accounted for 3D effects. This data was used as input for static loading analysis of the blade structural response (i.e. under steady current). This included comparison of a range of structural blade designs and different composite materials. Dynamic loading time series data were generated using the unsteady BEMT model (simulating wave-current loading) for input to fatigue modelling of the blade conducted at Newcastle. Collaborations with Southampton enabled a detailed comparison of modelling approaches (BEMT and actuator line) to quantify rotor performance and loadings. They jointly investigated field conditions, and agreed an analysis methodology to compare data from different sites to assess wave climates and the potential effects on turbine loading and performance across a range of real sea conditions. The outcomes of this investigation were fed into the static and dynamic structural modelling work to quantify blade performance under even and uneven loading conditions. Experimental studies at Southampton qualified the variance in tidal turbine rotor thrust and torque for different turbulent inflow intensities and length scales, demonstrating up to a 10% influence on device average power performance and loading.



Strathclyde Tribos group used two experimental rigs, an impinging jet rig and a slurry pot rig to explore erosion wear on scaled down tidal turbine blades. Wear maps were generated as a result to identify optimum performance conditions for the environment. The work at Newcastle focused on the development of a full mechanical and lifing model for the composite tidal turbine blades incorporating static loading and dynamic BEMT model loadings (from Strathclyde), realistic composite architectures and experimental material performance data. A multi-sample displacement controlled three point bend fatigue test rig was commissioned and used to generate data in air and seawater for a number of different composite materials including woven glass epoxy and foam core materials. High cycle fatigue life was found to be considerably reduced in the presence of sea water and the effect is more pronounced if the loading direction deviates from the fibre direction. Work at Newcastle determined realistic failure mechanisms for incorporation in the structural models. From the fatigue tests it became clear that micro-cracking in the matrix and delamination between plies are significant life-limiting defects. Strain mapping was used to look at the localisation of failure in the structure. Ingress of water into the composite structure was shown to enhance cracking as both water pressure in the cracks and salt deposition on crack surfaces can reduce crack healing.



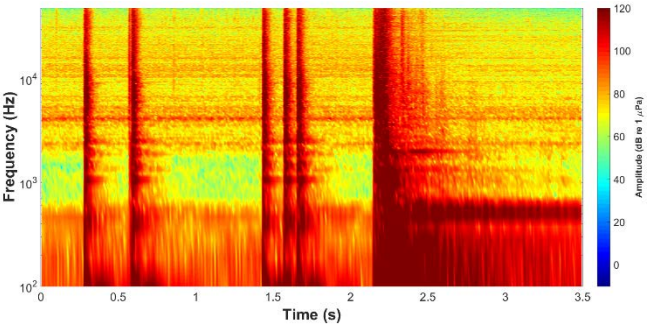
2.5 Novel marine energy systems and components

Core research at Exeter aimed to model and assess the performance and degradation of novel mooring materials and components to inform and develop a failure-based prognostic technique for moorings that will assist in the detection and prediction of failure. They have modelled, developed and tested novel mooring materials to understand component performance and degradation and inform a failure based prognostic model for moorings. The research uses data sets obtained from the open-water South West Mooring Test Facility (SWMTF) and their reliability test rig (DMaC) to increase understanding of performance, long-term behaviour, fatigue loading and reliability for both mooring components and monitoring systems.



They have assessed, tested and enhanced the performance of dynamic umbilical and mooring cables for marine renewable energy devices to address the design dilemma of high stiffness - high breaking load mooring systems that lead to spiralling cost. They have validated and demonstrated three main concepts of nonlinear mooring tethers, including a patented invention in collaboration with Lankhorst Ropes. They have developed and demonstrated the feasibility of acoustic emission monitoring of devices and moorings. Experimental tests on the DMaC facility have established the acoustic failure and degradation signatures for synthetic mooring ropes.

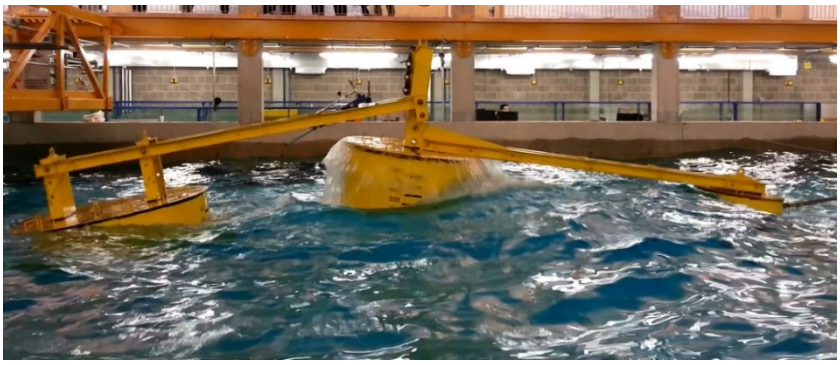
Research work on a novel mooring spring damper system has characterised materials and investigated endurance behaviour in large-scale experimental conditions. The material behaviour of the core material of the tether has been investigated with compression loading and long-term seawater exposure tests. This has resulted in the manufacture, bench- and field-testing of the mooring tether. Reliability assessment of novel mooring tether identified several key areas to improve the reliability of further development iterations.

Manchester collaborated with Oxford and Bath in the *Step Change for WEC through Floating Multi-Body Multi-Mode Systems in Swell (STEPWEC)* project aiming to design, analyse and optimise floating systems of approximately 10 MW capacity for wave energy conversion in swell and mixed swell/wind waves based. They specifically sought to explore the multi-mode response of two or more dynamically connected bodies and assess their interaction within an array.

A design was produced with three in-line floats with approximately half wavelength spacing responding predominantly in anti-phase. The bow float is tethered to a mooring buoy and the floats increase in size (diameter and draft) from bow to stern, facilitating natural alignment with the wave direction. The small

bow float and mid float are rigidly connected. The large stern float is connected by a beam to a hinge above the mid float where relative rotation between floats provides power to the PTO. The large stern float and the mid float have different heave resonance periods within the wave period range of a particular wave climate. The anti-phase heave motion of the bow and mid floats generates pitching motion in anti-phase with the stern float. The large anti-phase surge forcing between the mid and stern floats doubles power generation due to the moments about the hinge above mid float (shown by mathematical modelling). Broad band frequency response in irregular waves results. There are effectively no drag losses with rounded base floats shown by experimental and mathematical modelling.

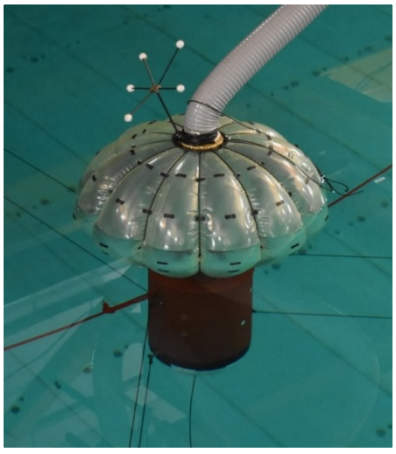


There is acceptable motion in extreme waves with negligible power generation. An upper limit on relative pitch motion is inferred from model tests at about ± 40^{o}. Experiments around 1:50 and 1:10 scale confirmed the validity of Froude scaling. Experiments were undertaken in the wave basin at Plymouth at both scales and in the Manchester wide flume at small scale (giving close results).

Frequency domain and time domain linear diffraction modelling (at Bath/Oxford and Manchester respectively) gave good predictions of response and power generally. However agreement for irregular waves was better than for regular waves possibly due to any basin reflections being averaged out in irregular waves. Agreement in multi-directional was also excellent. Multi-body models were extended to predict beam bending moments.

The excellent predictions by linear diffraction methods indicate that second-order effects are negligible. The float diameters were in fact made as small as possible without loss of energy capture to minimise cost and this reduces second-order trapping effects. In fact the good linear predictions extended to quite large waves (approximately 4 m full scale) and even extreme waves had only small nonlinear effects. Array results in regular waves using linear diffraction modelling showed the small influence of device spacing (above about one wavelength) and corresponding results in irregular waves were obtained.

The Plymouth project *The hydrodynamics of deformable flexible fabric structures for wave energy conversion* was collaborative with Southampton and aimed to investigate the hydrodynamics of flexible fabric structures for wave energy conversion. Their work assessed the hydrodynamics of the breathing action within a new device concept called the SQ series, by using semi-analytical and numerical models and by performing a series of physical experiments in the ocean basin within the COAST Laboratory at Plymouth. New concepts were developed that utilise the action of flexible fabric structures that deform under the action of waves to pump air between two chambers. The investigation of the different concepts has been considered through the development of new numerical models based on a semi-analytical approach and using the commercial code WAMIT with generalised mode modifications to take account of the flexible structure deformations. In parallel with the numerical model development, a series of scale model experiments were carried out in the COAST ocean basin at Plymouth University.



Three test campaigns were carried out to assess concepts SQ1, SQ2 and SQ3 at 20th scale. These tests involved design of a simulated air turbine PTO with air chambers designed to account for the effect of air compression at full scale. A novel pump system was designed to be exchanged for the PTO in the experiment setup for driven tests in which the air compression was driven to cause the device to

respond in still water and the resulting wave generation measured. Different tests were conducted: static tests, driven tests, and regular wave tests and a comprehensive dataset on response and performance was collected. The numerical models have been compared with the experiments and have given further insight to the hydrodynamics. It was found that the original hypothesis; that a flexible fabric structure that deforms in the waves would lengthen the natural period of response was confirmed both in numerical prediction and experiment. Use of deformable structures within different WEC types has been shown to alter their response characteristics and the complex dynamic response was predicted by the numerical modelling and observed in the experiment. This behaviour may be exploited for tuning and survival conditions and will be further investigated in the WETS project proposal.

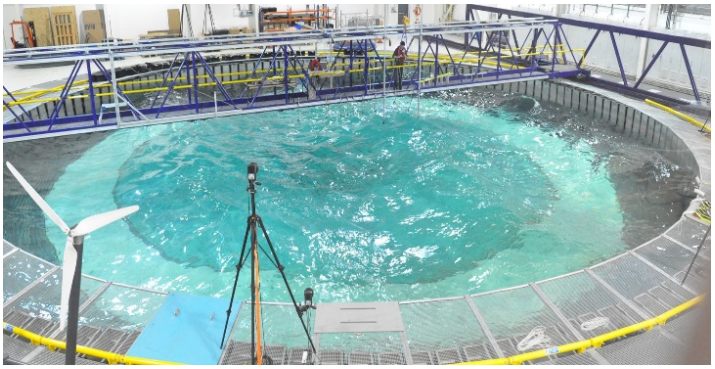
2.6 FloWave Ocean Energy Research Facility

Following preliminary work under Supergen Phase 2 (EP/E040136/1), the consequent award in 2010 (EP/H012745/1) provided insight into the combined generation of stable waves and current in test tanks. In early 2011 funding was secured from EPSRC (EP/I02932X/1) and the University of Edinburgh to construct the world's first circular combined wave and current basin at King's Buildings. This was further supported by Scottish Enterprise, and the FloWave facility was opened in 2014. FloWave has since achieved ISO 9001:2015 accreditation and is a member of the Association for Innovation, Research and Technology Organisations (AIRTO). FloWave also won the Scottish Renewables Innovation Award in 2014; the BusinessGreen Marine Energy Innovation of the Year Award in 2015; the EPSRC photo competition in the Equipment category in 2016, and is widely regarded as one of the world's most sophisticated facilities for ocean energy research.

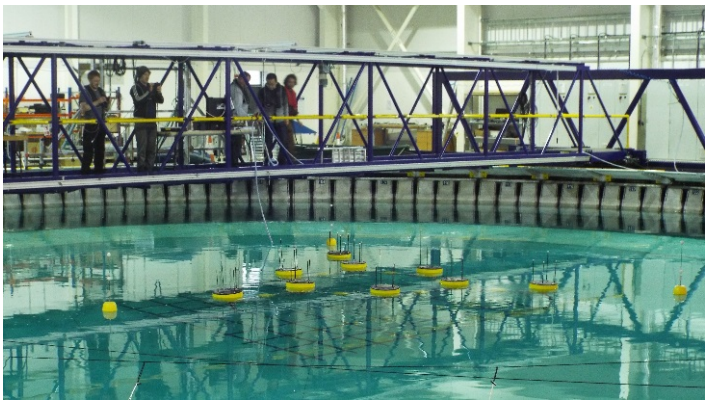
FloWave's design and construction included innovative engineering in partnership with Edinburgh Designs Ltd to allow the 168 force-feedback, active-absorbing, wave makers encircling the basin to operate both in the presence of flowing water, and with the 28 six-tonnes-per-second flow-drive units of the current generation system. These introduce current with the correct boundary layer profile at low levels of turbulence intensity and, subject to correspondingly higher turbulence levels, at faster flow speeds up to and including those equivalent to the Bay of Fundy in Canada. The circular disposition of wave-makers and flow-drives allow the generation of waves up to 0.5 m height and the introduction of currents up to 1.6 ms^{-1} in any individually absolute and relative direction. A rising tank floor and 5t overhead crane enable quick and easy installation of individual devices, or arrays of wave or tidal current generators.

This fundamental work in fluid mechanics (supported by EP/H012745/1) combined experimental work and computational fluid dynamics simulations to provide a robust system that was constructed from a combination of off-the-shelf components and custom manufactured components to provide a high TRL solution for combined wave and current generation. Perhaps the most important feature of the facility is the rapid settle time that can be achieved due the encirclement by active-absorbing wave-makers and the complete absence of static reflecting surfaces. With settle times between tests typically less than 3-4 minutes the achievable throughput of tests in a day is several times higher than that achievable in more traditionally-configured facilities. FloWave's complete circle of wave makers has furthermore facilitated the development of a low-pass floating wave filter suite that can be deployed to absorb high frequency waves too small to be absorbed by the system and/or reflected from models and equipment under test.

FloWave has enabled new science to be undertaken, particularly in the area of characterising realistic multi-directional, bi-modal sea-states, and these also in combination with fully developed tidal current flows from any point of the compass or relative angle. This has led to the in-house development of new techniques for re-creating representative site-specific sea-states, benchmarked against representative 4 years of wave-rider buoy measurements from EMEC's Billia Croo site that are endorsed by developers highly experienced



with the site. This work is influencing the creation of a standardised set of sea states for Wave Energy Scotland testing, and allows a direct inter-comparison of the performance of different wave energy converter models exactly as if the full scale device were really deployed at that site. With this technique further developed, FloWave now has a world-unique capability to carry out replication of site-specific conditions for any location for which there is sufficient data.



Other work has included the development of new measurement techniques and instrumentation for characterising flow and turbulence, tests examining cable behaviour and treatment at un-trenchable tidal current sites, and hands-free station-keeping 'auto-pilot' software for ROVs operating in simultaneous wave and current. Since completion of initial commissioning in April of 2014 FloWave has entered scope and contract discussions with approximately 50 companies and academic groups, completing more than 35 test campaigns for PhD and EngD students, academic research projects and commercial companies. Commercial testing has been undertaken for UK and international clients, including: Albatern, Nova Innovation, QED Naval, WEPTOS, Carnegie Wave Power, Rockland Scientific, Sendekia, TFI, EnerOcean, W2Power, SeaByte, SeaTronics, BlueFin, FlexMarine Power, AWS, Mocean, Quoceant and Joules Energy.

These commercial tests cover proof of concept tests, design verification studies, fundamental device hydrodynamics, mooring load simulations, station keeping trials, failure mode analyses, performance refinement, survivability and operational de-risking. Wave energy converters, tidal energy converters and floating offshore wind systems have all been tested, along with ancillary and support equipment including novel sensors, sensor arrays, and ROVs. Most recently FloWave has delivered a series of qualification tests for five clients of the eight funded by the Wave Energy Scotland stage 1 novel wave energy converter call.

Such controlled environment laboratory tests have formed a key milestone in qualifying early stage designs for further development, and help increase the performance and reliability of individual devices as well as projects. FloWave participated in the EU Marinet trans-national access project, providing 7 weeks of testing to European teams from Spain, Denmark and Ireland. It will also participate in Marinet-2 expected to start early in 2017.

3 Capacity Building

3.1 Phase 3 – Doctoral Training Programme

Led by Prof Mueller at Edinburgh Phase 3 sponsored 14 PhD students on the UKCMER DTP across 11 partner universities to integrate the associate partners with core activity. Their areas of study, stage of completion and destinations are shown below.

- Tessa Gordelier (Exeter): "**Enhancing wave energy developments through mooring system reliability assessment**"; graduated 2015, now PDRA at Exeter.
- Edward Ransley (Plymouth): "**Survivability of wave energy converter and mooring coupled system using CFD**"; graduated 2015, now PDRA at Plymouth.
- David Crooks (QUB): "**Development of Nonlinear Hydrodynamic Terms in an Oscillating Wave Surge Converters Time Domain Numerical Model**"; graduated 2015, now PDRA at Edinburgh.
- Alex Olczak (Manchester): "**The Influence of Waves on Tidal Stream Turbine Arrays**"; graduated 2016, now working for Wind Prospectus in Bristol.
- Katie Gracie (Strathclyde): "**Fixed-pitch blades for passive-feather power regulation of horizontal axis tidal stream turbines**"; graduated 2016, now working for Sgurr Energy.
- Thomas Nevalainen (Strathclyde): "**Hydrodynamic loads on tidal stream turbines caused by waves and shear current profiles**", will graduate 2017, now working for QED Naval.
- Thomas Lake (Swansea): "Computational Modelling of Interactions of Marine Mammals and Tidal Stream Turbines", will graduate 2017.
- Susannah Cooke (Oxford): "**Enhanced array design for tidal power generation**", will graduate 2017.
- Jose Barajas-Solano (Edinburgh): "**Electromagnetic bearings for linear electrical generators in direct drive WECs**", research complete, will graduate 2017, now working as PDRA at Edinburgh.
- Andrew Want (Heriot-Watt): "**Methodologies for the prediction and monitoring of environmental impacts following deployment of wave and tidal energy devices against an expected background of climate change on the marine ecosystem**", recent award, submission in 2017.
- Daniel Richardson (Lancaster): "**Multi-axis point absorber wave energy converters**", recent award, submission in 2017.
- Daniel Coles (Southampton): "**Energy extraction by large tidal stream turbine arrays at locations around the Channel Islands**", recent award, submission in 2017.
- Anna Garcia-Teruel (Edinburgh): "**Cost and performance optimisation of wave energy converters**", more recent award co-sponsored by the Scottish Energy Technologies Partnership, submission 2019.
- Maria Pafi (QUB): "**A GIS-based Decision Support System for marine spatial planning**", more recent award co-sponsored by the Cullen Foundation, submission in 2019.

Many of the doctoral students sponsored across the original core and associate partner universities have now graduated and taken employment as post-doctoral researchers or in the sector. All others are on track to do so. Many of the original research staff have been promoted to full-time lecturing posts, and there is a healthy reward-based recognition of junior and mid-career staff being promoted to more senior positions. Copies of the theses are, or will be, available from the universities.

Additionally, though the course of phase 3, UKCMER staff have been able to secure and use consequent funding to engage in EngD and PhD training through the ETI-EPSRC IDCORE and CDT programmes in offshore renewable energy, collectively training another 100 key staff for the sector.

3.2 EPSRC:ETI Industrial Doctoral Centre in ORE (IDCORE)

In 2011 the Universities of Edinburgh, Exeter and Strathclyde, supported by the Scottish Association for Marine Sciences (SAMS) and HR-Wallingford were awarded funds (EP/J500847/1) from ETI and EPSRC to form the *Industrial Doctorate Centre for Offshore Renewable Energy (IDCORE)*. Led by Prof Ingram of

UKCMER at Edinburgh, the partnership offers a unique combination of experience in research, development and knowledge exchange with major industry stakeholders in offshore renewable energy and offshore engineering in the naval architecture and oil and gas sectors, complemented by the extensive experience of SAMS in the environmental and societal impacts of offshore renewable energy projects. The first research engineers arrived in January 2012 with subsequent cohorts starting in September of 2012-15. They participate in a first year programme of 12 mandatory training courses covering maritime structures, electrical and mechanical engineering, resource analysis, project economics, network integration, marine biology, laboratory testing and a group design project to prepare them for a three year, industrially based, research project. Ultimately they graduate with an EngD, jointly awarded by the three partner universities. The programme is extremely popular attracting more than 100 applicants each year for the 10 places offered. Appropriately and highly qualified applicants must pass a rigorous interview process before being offered a place. Such is the demand for graduates of this nature and the high selection threshold, every year more projects have been offered than there are students meeting the standards necessary for guaranteed progression to employment. The IDCORE programme is closely integrated with the activities UKCMER and many of the companies sponsoring projects have been recruited through links developed by UKCMER.

To date 55 research engineers have started the programme, 5 have graduated, 7 are about to submit, 5 are taking the training programme and 38 are currently working on their industrial research projects. IDCORE research engineers are working across the offshore energy sector in companies ranging from SMEs to very large enterprises. They are engaged in work developing the next generation of machines for original equipment manufacturers, developing standards for classification societies, devising test procedures and methodologies, building tools to support investment decisions and optimising O&M strategies. Sponsoring companies include: EDF, Uniper, Alstom, ETI, ORE-Catapult, FloWave, Wave Energy Scotland, Albatern, Zyba Renewables, SAMS, HR-Wallingford, Tidal Energy Limited, Concrete Marine Solutions, Lloyds Register, DVN GL, JBA, Sgurr Energy, and Sustainable Marine Energy. Several students started projects with either Pelamis Wave Power or Aquamarine Power and have now transferred to other sponsors following the collapse of these companies. Beyond the obvious impact of providing highly skilled, highly motivated research engineers to industrial companies to work on real, highly challenging, problems – and consequently delivering economic impact, IDCORE research engineers continue to produce high impact journal papers and to present internationally leading work to major international conferences. At the 2016 International Conference on Ocean Energy, Anthony Gray won first prize in the IEA-OES poster competition for “Identifying Key O&M Strategy Considerations for a Wave Energy Array: A Case Study on Pelamis”. Many of the technical sessions at this conference, which has a specific focus on real industrial problems, were dominated by presentations from IDCORE research engineers.

The success of IDCORE has led directly to a two-year, no-cost, extension which will has seen 5 research engineers recruited this year and we expect a total of 15 additional research engineers recruited, trained with and employed by the sector.

3.3 Centre for Doctoral Training in Wind and Marine Energy Systems

With funding from EPSRC under award EP/L016680/1 Strathclyde and Edinburgh Universities collaborate in the *Centre for Doctoral Training in Wind and Marine Energy Systems*. Led by Prof Leithead of Supergen Wind at Strathclyde with Prof Mueller of UKCMER at Edinburgh, this programme will intensively train 40 PhD students for careers in the sector from academia to industry. It is collaborative with many industry partners, including Atkins; EDF Energy; Energy Technology Centre; The Energy Technology Partnership; FloWave TT Limited; Gamesa; Garrad Hassan & Partners Ltd; Lloyd's Register; National Renewable Energy Centre; Offshore Renewable Energy Catapult; Renewable Energy Systems Ltd; Romax Technology Limited; Scottish and Southern Energy (SSE); Scottish Power; SgurrEnergy Ltd; Siemens; Sinclair Knight Merz (Europe) Ltd Subsea 7 Limited; Technip Offshore Wind Ltd UK. There are three cohort years still to seek applicants.

4 Output, Impact, Engagement and International Articulation

4.1 Dissemination of Output

The outputs, listed by workstream and alphabetically in Appendices 2&3, have disseminated results on paper, electronically, verbally at conferences and seminars. Wider dissemination and knowledge exchange has been delivered through industry engagement, interaction with policy and standards agencies and processes and international articulation, as described in the next three sections.

4.2 Impact

Internationally leading work by the UKCMER partners has led to patents, major publications and significant engagement with industry. The following patents have, or are being, filed

- Miller R. J., 2015 (in Preparation) Tidal Turbine Load Shedding Device
- Johanning, L. 2014 (US No 8,807,060 B2) 2014 Mooring Limb
- Stansby, P. 2013 (UK No PCT/GB2013/050787) Surge based wave energy converter
- Johanning, L. 2011 (EU No EP11703043.7 - Filed) Mooring Limb

In addition, a patent is expected on a novel wave energy converter that uses a dielectric elastomer as the PTO system.

Many papers have won prizes. Edmunds et al investigated a number of common array configurations for tidal turbines using a highly efficient model embedded in a CFD code. The tools were used in the development of the Montrose array with Juno Energy for GSK, resulting in the Quotient project (C001822, part of the HEFCW LCEE National Research Network). The paper was named best paper at the Marine Energy Technology Symposium (Washington, 2016) and is currently listed as one of the Journals most highly cited articles. Sellar, Harding and Richmond's work on a convergent beam acoustic Doppler profiler provides a mechanism for flow and turbulence to be characterised in a small volume near a tidal turbine. Comparisons with traditional ADCPs show an order of magnitude reduction in the realisable length scale with improved correlation, and a 47% reduction in Doppler noise. The technique was demonstrated at the EMEC tidal site using the GE DeepGen 1MW turbine and has been deployed at the FORCE test site in Canada. The paper was awarded the 2015 Journal of Measurement Science & Technology Outstanding Paper Award for by the IOP.

The *Terawatt* GC project developed the first-ever methodology to investigate the 3-dimensional morphodynamic impacts of tidal turbine arrays and this now allows The Crown Estate, Scottish Natural Heritage, Marine Alliance for Science and Technology in Scotland and the marine renewable energy developer community to use them in site selection, planning applications, impact mitigation and turbine array design. TeraWatt also developed a geo-spatial model that allows the investigation and quantification of the effects of wave energy extraction across very large arrays with which the energy-environmental impact due to change of the surrounding wave climate can, for the first time, be explored. They produced a toolbox of outputs covering the data acquisition, processing and validation used in the study, realistic array scenarios and development of wave and tidal modelling, including means of introducing energy harvesting within these. The book is freely available to wave and tide, device and project developers. This work led to the EPSRC Grand Challenge *FlowTurb* project.

Work at Strathclyde has identified very aggressive large-scale rotational vorticity in the vertical plane penetrating down the water column at the wave frequency. Longer period ocean waves penetrate even deeper down the water column inducing large axial velocity variations in flow velocities impacting on the rotors of turbines. This acts on the blade systems, power take offs and structures of the devices exposing them to cyclic, regular and extreme mechanical loadings and damaging torque pulses in the drive train that could lead to failure. A combined wave-current unsteady BEMT model coupled with a higher fidelity, six degree of freedom, finite element drivetrain model has been used to explore the range of cyclic loading conditions experienced by the rotor to investigate and quantify the influence on loading, station keeping, and power transfer in the drive train. Work at Edinburgh on the GE DeepGen 1MW turbine deployment at EMEC measured, processed and assimilated real-time field data that confirms the very significant effects of the wave regime on the near-field flows around commercial scale turbines.

The performance of horizontal axis tidal turbines has been considered both in respect of fatigue and extreme loads. The Cardiff Grand Challenge project *The Effects of Realistic Tidal Flows on the Performance and Structural Integrity of TSTs* considered the effects of "real" complex high energy flows and their influences on tidal turbines, through a number of computational tools and condition monitoring methods. Oceanographic models and data for a Welsh deployment site show the flow direction fluctuates by $\pm 20^{\circ}$ to the main flow, experimental and numerical results indicate that the shaft power reduces by ~20% for $\pm 20^{\circ}$ misalignment with a comparable reduction in thrust and a threefold increase in shaft bending moment. Wave-current interactions only make this worse. This work is now being extended to arrays of machines under the EPSRC GC *Dylotta* project.

Edinburgh staff have developed a fully-coupled bi-directional wave-to-wire model. The model has also been used in the Hydralab IV "WECwakes" project (which also involved Queens and Manchester). WECwakes tested an array of 25 model wave energy converters in a wave basin to produce the first and currently largest such set of tests. The model has also been extended for the PolyWEC (FP7-309139) project to consider machines where a deformable dielectric elastomer is in direct contact with the water. A patent on this technology is expected shortly. The wave-to-wire model was also used in the Danish SDWED project to investigate the global coordinated control of a multi-float Wavestar device. Due to the success of the time-domain mode funding was won from Wave Energy Scotland's PTO and novel devices calls. The model is also being employed in the H2020 OPERA, ETIP and WaveBoost projects and forms part of the DTOcean projects suite of design tools.

Media and public interest in the FloWave Ocean Energy Research Facility is acute with events held during the Cockburn Associations "Doors Open Day" and the Edinburgh Science Festival regularly selling out. FloWave continually receives requests for visits and demonstrations for inbound missions organised by Scottish Development International – hosting delegations from, e.g. Chile, China, India, and Japan. The facility is visited regularly by high level delegations to the UK including, the late former President of India, Dr. APJ Abdul Kalam, the Deputy British High Commissioner for India, and most recently the US Department of Energy attaché in London, accompanied by staff members of the US House of Representatives Appropriations Committee on Energy, Water, and Development.

4.3 Industry Engagement and Knowledge Exchange

Over 40 partner companies, from multinationals to SMEs, have continued to engage with UKCMER universities across every theme. Selected examples follow.

The availability, accruing know-how and facilities at the FloWave Ocean Energy Research Facility in Edinburgh have enabled engagement with Albatern, Nova Innovation, QED Naval, WEPTOS, Aalborg University, Carnegie Wave Power, Rockland Scientific, Sendekia, Scotrenewables, TFI, EnerOcean, W2Power, SeaByte, SeaTronics, BlueFin, Sustainable Marine Energy, and FlexMarine Power. This has included development and testing of wave and tidal generation technologies, mooring systems, active anchors, autonomous underwater vehicles, floating offshore wind platforms and novel instrumentation and measurement techniques.

Edinburgh and Exeter lead and partner, in the EU flagship research project DTOcean, alongside 18 and European and international organisations in the development of optimal tools for array planning in the MRE industry. Including: Prysmian provided electrical specification data in order to allow Edinburgh to study the techno-economic impacts of different array layouts and transmission options for marine energy farms. IT Power and Deme and Scandia National Lab (US) have provided a detailed analysis of the different intra-array network layout options for marine energy farms. This was used as one of the inputs to the techno-economic optimisation tool developed by Edinburgh – the tools are being validated by Vattenfall and Scottish Power Renewables.

Through the use of the DMaC test facilities and implementation of the Falmouth Bay marine energy demonstration site (FabTest) Exeter has strong engagement with industry partners such as Fred Olsen Renewables, Mojo Maritime, A&P, AWS, TTI, Bluewater, DNV-GL, JDR Cable Ltd, Aquaterra Ltd, Severn Subsea Technology, Lankhorst Ropes and CPNL Engineering. Collaborative work with Optoelectronic Manufacturing Corporation has sought to develop innovative solutions for condition monitoring in mooring ropes. As a partner on the successful transnational access H2020 project 'Marinet', Exeter has

been providing the Dynamic Marine Test Facility (DMaC) and the Falmouth Bay Test facility (FaBTest) as test beds.

Exeter have developed the Mermaid software package with Mojo Maritime (who are now part of Fisher Group). The software is now a fully commercial product that is used on major projects such as Meygen as well as by large enterprises for the implementation of O&M strategies. Use of Exeter's DMaC test facilities and the Falmouth Bay marine energy demonstration site have enabled the Fred Olsen Renewables company to achieve the longest continuous deployment of any floating Wave Energy Device to date. This work has provided essential power performance and durability characteristics enabling Fred Olsen to move towards commercial deployments at Wave hub. Work at Exeter has also supported the development of the Mojo Maritime HiFlo-4 tidal turbine installation vessel.

Queens and Schottel have been measuring noise emissions of a full scale tidal device in Strangford Lough, where they have been able to provide input into the appropriate methods in obtaining noise data for Minesto. Partrac carried out turbulence survey work for Tidal Energy Limited, who have deployed a 400kW turbine in Ramsey Sound, worked with Swansea to analyse and interpret data they had collected. Staff at Swansea are members of the MEP working group and also manage the "LCRI" wave rider buoy at the demonstration zone. Morlais Energy manage the 100MW Crown Estate North Wales demonstration zone and are working with Swansea to develop array layout models based on UKCMER science.

Tidal technology and rotor developers, ResHydro Ltd, Nautricity Ltd, Airborne Composites BV, are providing insight and feedback through Strathclyde on the tidal environmental conditions they are designing their product to operate within, together with the current engineering design methods adopted in the development of the product. EMEC is providing access to site data against which realistic operating conditions can be benchmarked, within the program of work. Lloyd's Register, RES Ltd, are providing engineering design feedback and the applicability of the design/decision support tools being developed to engineering practice.

Work undertaken by Queens (physical model testing) and Manchester Metropolitan University (numerical modelling) feeds directly into the design of surging flap-type wave energy converters. Findings obtained are used to suggest important decisions in the design process in terms of reducing and mitigating the most severe extreme loads. The development of accurate and precise physical testing facilities has also led to improvements in how extreme load testing will be undertaken in the future. The project team worked closely with WavEC Offshore Renewables to place the research findings into a day-to-day consulting context. This has helped the development of partially nonlinear and computationally efficient models fit for engineering design. To accelerate this process, a WavEC team member was seconded to Imperial College; this four-month placement having been supported through additional EU KIC funding.

Throughout the EloWEC project, a significant amount of progress was made in relation to extreme wave loading. The methodologies established reach well beyond the wave energy sector, with applications to many static and dynamic marine structures. New experimental techniques suitable for the measurement of extreme loads have been developed. Numerical models suitable to impact loading cases were also advanced. In addition, the project has provided inputs to a new Joint Industry funded Project (JIP) and revised design guidance in respect of the relevant met-ocean conditions, particularly the occurrence of breaking wave loads.

ANSYS have provided HPC research licences to Cardiff along with valuable technical advice, enabling the ongoing and challenging computational modelling work there to develop a transient model of the 2-way fluid structural interaction of a tidal turbine. Bosch Rexroth supplied the specialised electrical generators for the model tidal turbines and bench top equipment for condition monitoring investigations and provided exceptionally valuable technical support and advice. National Instruments provided instrumentation along with technical advice and training. Gurit provided valuable technical advice on the structure of turbine blades and Tidal Energy provided the turbine to test new blade designs. Other collaborators included: Crown Estates; Mabey Bridge Ltd; Marine Current Turbines; Natural Resources Wales; TATA and Minesto.

The development of StepWEC and the XMED project at Manchester has been strongly supported by EDF, DNV-GL, ALSTOM Ocean and EON. DNV have been working with Imperial and Waveroller on the design and development of their full scale device (another OWSC). QUB have provided advice on extreme load testing requirements for this work, and have given feedback on the extreme loads experienced by the full scale Oyster device. The Step-WEC project investigated the M4 wave energy converter, developed with capture widths close to the theoretical maximum for a multi-mode point absorber. Linear diffraction models (developed by Bath and Oxford) have been shown to give good power and motion predictions in operational conditions. These models together with experiments have enabled predictions of cost and LCOE similar to that of offshore wind energy and could be further reduced by design optimisation and PTO.

Oxford and UCL are supported by collaborations with ARUP, Ramboll, IT Power consultants and HR Wallingford both in ongoing work and in the preparation of new submissions. BP Exploration has provided hindcast and measured wave data to Oxford that has been pivotal for the work on the long-term variability of the wave resource and also the extractable annual power from the M4 wave power machine. BP are also very interested in their extreme wave estimates (100-year and rarer) at locations where they have platforms.

Cambridge operates the low-TRL hydrodynamics development laboratory in partnership with Rolls-Royce and has been developing a load shedding device with Alstom, who are now supporting a PhD studentship through the EPSRC-CASE scheme. Tidal Energy Limited are working with Cranfield University to develop understanding of ADCP data and device hydrodynamics through enhanced BEM simulations and have provided ADCP data for analysis. Cambridge are in preliminary discussions with Nortek who are interested in the commercialisation of a novel turbulence-measuring probe.

Plymouth have collaborated with Griffon Hoverwork who have provided material for construction of SQ models and manufacturing of SQ flexible components and connections.

The TeraWatt and ECOWatt Challenge projects led by Heriot-Watt enjoy include MCT (Atlantis), Scotrenewables, CNC Asset, E.ON, MeyGen, Marine Scotland Science, Marine Management Organisation, Marine Scotland, The Crown Estate, Marine Alliance for Science and Technology in Scotland who provide data, and share comparable modelling studies. Scotrenewables have assisted in a comparison of our model outputs with those of their CFD model, and this has led to a further collaboration with them under an accelerated impact award linked to TeraWatt and EcoWatt2050.

4.4 Engagement with Policy, Standards and Regulation

The UK has the best-connected and most enabled innovation system to support the deployment of marine energy technologies in the world. UKCMER core and GC partners serve on 16 regional, national, European and Global policy and standards agencies. Jeffrey now vice-chairs the IEA Ocean Energy Systems Collaboration Agreement. Edinburgh serves on the Energy Technologies Institute Strategic Advisory Group. Wallace chairs the Academic Research Advisory Group of the Offshore Renewable Energy Catapult and has worked with the Research and Innovation Director to produce and gain approval for their Research Strategy and Academic Engagement Plan. This will make provision for the co-sponsorship of six Industry Professorships in key knowledge areas across UK universities in offshore wind, wave and tidal energy. Jeffrey and other UKCMER staff have provided expert input into the formation of the Wave and Tidal TINAs. UKCMER also receives advice, guidance and support from the Renewables UK Marine Strategy Group where Jeffrey, from Edinburgh represents the work and interests of UKCMER. Masters chaired the Advisory Board of the NERC Marine Renewable Energy Knowledge Exchange Programme.

Regional initiatives such as Wave Energy Scotland (WES) are now investing in research to support the development of components, subsystems and technologies. Jeffrey and Edinburgh research staff are part- and wholly-seconded to provide technology and innovation policy advice to WES. There have been other investments in the South-West (PriMare) and in Wales (LCRI). Johanning and Masters have provided similar support in these organisations. Through UKCMER, many academic and research staff participate in BSI PEL114 and IEC TC114, leading and contributing to the development of many parts of IEC standards in the 62600 - Marine energy: Wave, tidal and other water current converters series.

UKCMER universities have interacted with regional, national, European and global innovation and policy bodies. The Ocean Energy Systems (OES) Energy Technology Initiative is an intergovernmental collaboration between countries, which operates under a framework established by the International Energy Agency (IEA) in Paris. Jeffrey, Network Manager from Edinburgh is Chair of the OES collaboration agreement on behalf of the UK Department of Energy and Climate Change. In January of 2015, the Edinburgh seconded Jeffrey to lead the research and innovation strategy for Wave Energy Scotland, providing a direct link to the UKCMER international academic expertise and insight into the future innovation and development needs of wave energy. Jeffrey has secured funding from WES and the Scottish Energy Technology Partnership to appoint a Knowledge Exchange and Business Development Executive, working alongside and with UKCMER. WES will also support tensioned awards (up to £250K) of flexible funding in the 4th Phase of UKCMER during 2017 to further strengthen the link between UKCMER research and wave energy development.

UKCMER and other staff have planned, prepared, and executed the first three funding calls for research contracts in Structural Materials and Manufacturing Processes, secondary energy conversion technologies (PTO systems), and Novel Wave Energy Converter concepts.

OCEANERA-NET is the Ocean Energy European Research Area Network funded by the European Union through Framework Programme 7. It comprises a network of 16 national and regional funding agencies that coordinate activity between European countries and regions to support research and innovation in the ocean energy sector. UKCMER staff hold a position on the ERA advisory board and have been closely involved with OCEANERA-NET to coordinate funding calls and establish links between the research activity and the research funders. UKCMER staff have also advised strategic input on the recently awarded ERANET Co-Fund for ocean energy.

The European Energy Research Alliance (EERA) Ocean Energy Joint Programme brings together the main research providers in 9 countries and is based around six key research themes developed from existing research roadmaps which identify the critical areas of research required for the successful growth of the industry. The programme ensures coloration at an EU level and avoids the duplication or replication of research efforts. Edinburgh leads and coordinates the EERA Ocean Energy Joint Programme, allowing UKCMER to efficiently to provide expert input in the development of the H2020 programme for ocean energy.

Ocean Energy Europe (the largest network of ocean energy professionals in the world) acts as the main link between Europe's ocean energy industry and the EU institutions (European Commission, European Parliament, EIB etc.) and EU Member States. Edinburgh represents the UKCMER membership on the Ocean Energy Europe Board, with several other UKCMER members actively contributing to the prioritisation of research topics and technology improvements identified by the ocean energy industry and research community. These efforts formed the technology chapter of the ocean energy roadmap which will help accelerate deployment in the ocean energy sector.

Jeffrey serves on the EU expert advisory group for the Ocean Energy Forum Strategic Roadmap, involving key government, industry and academic stakeholders from across Europe to develop and produce a Strategic Roadmap for the development of the sector which is widely endorsed by industry, the public sector and civil society.

UKCMER partners across the TeraWatt and ECOWatt Challenge projects work closely with the Marine Management Organisation and Marine Scotland (Policy Branch) and The Crown Estate, who all serve on the Steering Group. The Marine Alliance Science and Technology Scotland (MASTS) chair the Steering Group Meetings and Marine Scotland organises outreach and knowledge transfer/exchange activities with developers.

Researchers from Exeter contributed to the development of standard document IEC TS 62600-10, Marine Energy – Wave, Tidal and Other Water Current Converters – Part 10: Assessment of Mooring System for Marine Energy Converters. Spinneken (Imperial College) led the development of tank testing guidelines through the framework of IEC-PT62600-103 “Guidelines for the early stage development of wave energy converters” to which Davey (Edinburgh) also contributes. Ingram (Edinburgh) worked on the development

of "IEC TS 62600-1, Marine Energy – Wave, Tidal and Other Water Current Converters – Part 1 Terminology" and is now contributing to the team preparing the international standard. These guidelines are believed to lead to cost reductions of new technologies, and to increase investor confidence by adopting a structured development approach.

Queens works with the Northern Ireland Environmental Agency where their knowledge and modelling tools are used in obtaining site licenses for testing scaled devices in Strangford Lough. Strathclyde is a member of the Scottish Renewables Marine Working Group, Scottish Government Marine Energy Group and Wave Energy Scotland to provide policy and regulatory advice to set the boundary conditions in which tidal technologies will operate. The Queens PDRA is convenor of the IEC committee for the development of standards for wave energy resource assessment and characterisation that includes members from UK, Ireland, USA, Canada, Japan and Spain. He is also UK principal expert on the IEC committee for the development of standards for the power performance assessment of wave energy converters, and inaugural convenor of the International Nemoh Developers Group. Nemoh is an open-source boundary element solver that can be used for modelling WECs and arrays. The use of boundary element solvers in the numerical modelling of WECs is ubiquitous and the provision of an open-source tool means that new companies can more easily access the tools vital for the development of a WEC. The Nemoh Developers Group is dedicated to improving the functionality and public accessibility of the open-source tool.

Cardiff and Bangor are working with the Crown Estates and Natural Resources Wales on the environmental modelling of the Welsh coastline. Wales Higher Education Brussels (WHEB) promotes Welsh Universities' higher education and research in Europe and provides access to European Commission policy makers. The WHEB team has a close working relationship with the Welsh MEPs as well as EC officials and the UK Permanent Representation to the EU. Masters (Swansea) has been a member of the WHEB working group whose main aim is to engage strategically with EU policy and funding opportunities, build on their extensive network of contacts in academia, industry and the European Institutions, and to promote Welsh research expertise in these areas. The work at Swansea provided the scientific basis for an industry in Wales and the recent development of two 100MW commercial demonstration zones, leased by the Crown Estate and backed by €100m demonstration funds from WEFO ERDF.

Marine Scotland Science (MSS) are full project partners on EcoWatt2050, having scoped, within the TeraWatt consortium, the key research questions to address policy needs. MSS were responsible for the holding and provision of all data being used in the project via an accessible data store. The development of device placing within the very large scale array developments foreseen in EcoWatt2050 has also been a task undertaken by Marine Scotland Science. The Marine Management Organisation and Marine Scotland (Policy Branch) serve on the Steering Group, The Crown Estate also is a Steering Group Member. MASTS are responsible for chairing the Steering Group Meetings and with Marine Scotland for organising outreach and knowledge transfer/exchange activities with the developers.

4.5 International Articulation

Establishing wave and tidal technology, its supply chains and international sectors is a global challenge that will only be met by working in international partnership. Supergen Phases 1 & 2 and Phase 3 UKCMER have operated an International Network since 2003. Core staff have led or assisted in the creation of strategic collaborative R&D programs, technology and deployment roadmaps, internationally for the IEA-OES and in many of the countries below, and have led the establishment of essential IEC standards. Edinburgh and other UKCMER partners routinely and regularly receive inward missions from all over the world, brought by UKTI, FCO, Scottish Development International and others. This section describes the deeper articulations with other countries.

Europe - Edinburgh leads the DTOcean collaborative project funded by the European Commission under the 7th Framework Programme for Research and Development, more specifically under the call ENERGY 2013-1. It gathers 18 partners from Ireland, Spain, United Kingdom, Germany, Portugal, France, Norway, Denmark, Sweden, Belgium and USA. Edinburgh and Plymouth were part of MARINET – Transnational access for marine renewable energy test facilities – a European project providing five periods of access to FloWave and the COAST basin for wave energy developers, a hybrid floating offshore wind/wave energy platform and mooring arrangements for a floating tidal turbine (WEPTOS, CETOW, PolyWEC, W2Power

and ScotRenewables). Consequent to the operation of IDCORE, Edinburgh was invited by the Danish Ministry of Education to contribute to a meeting exploring new directions for PhD students in Copenhagen. Forehand at Edinburgh chairs the European WECAN (Wave Energy Converter Array Network) within which researchers sharing results across Europe will inform the recently formed IEA-OES Annex VI on verification and validation. The network consists of international researchers, currently including members from the UK, Ireland, France, Spain, Belgium and USA. The network holds an annual symposium and was key in the formation of the WECwakes project (a HYDRALAB funded project that modelled a large array of WECs in the DHI wave basin). The Hydraulics and Maritime Research Centre (University College Cork, Ireland) is collaborating with Swansea on the MARIBE project, which is considering techno economics in the marine economy. Edinburgh and Plymouth are partners in the Horizon 2020 project WETFEET: Wave Energy Transition to Future through Evolution of Engineering Tools, 2015 – 2018 led by Wave Energy Centre (WAVEC), Portugal with collaborators in UK, Portugal, France, Italy, Austria and the Netherlands.

India - Edinburgh worked with the FCO India UK Science and Innovation Network to win Global Partnership funding to take UKCMER staff on a marine energy mission to Ahmedabad, Chennai and Kolkata. This included a UK-India R&D Scoping Workshop, a site visit to the Sundarbans Delta and workshops and meetings at IIT Madras, Anna University, IIT Kharagpur and Jadavpur University. This has since led to a consequent knowledge exchange and capacity building award, to explore the development of mini-tidal current power for rural electricity supply on the Sundarbans Delta, within which there has been a project scoping, knowledge exchange and training workshop. Local stakeholders include the WWF and West Bengal Renewable Energy Development Agency. Edinburgh also secured UKIERI funding to support knowledge exchange visits between and to IIT Bombay and the National Institute for Oceanography Goa. Meetings in Chennai, Bombay, Kolkata and Panjim have resulted in the Indian Academics now aiming to establish an India Ocean Energy Association. More recently Edinburgh has completed, with Jadavpur University, a tidal resource and energy demand assessment of a localised area in the Sundarbans Delta and held a stakeholder consultation workshop with 20 participating agencies from West Bengal.

Japan - Edinburgh led a mission to Nagasaki Prefecture in Japan that included the signing of an MOU with Nagasaki University to cooperate on marine energy activities, meetings with the Japan Society for Marine Renewable Energy, the Nagasaki Marine Energy Cluster and Nagasaki Prefecture Government. Seminars at Hiroshima, Hokkaido, Nagasaki and Nihon Universities have presented the work of and opportunities to work with UKCMER. Ongoing work with Hiroshima by an Edinburgh PhD student is investigating underwater acoustic tomography as a non-intrusive method to characterise the flow patterns in FloWave.

Chile - Edinburgh organised and ran an Ocean Energy R&D Scoping workshop with academics from Chile, hosted by Pontifical University Catolica de Chile (Santiago) and had meetings with PUC, Conicyt, CiFES and ENEL/DCNS to explore UK partnership with the Marine Energy Research and Innovation Centre (MERIC) just being set up in Chile. This also led to participation by PUC in a grand challenge bid. Strathclyde also collaborates with PUC on erosion-corrosion modelling. Edinburgh has established collaborations with MERIC and relationships with Fundacion Chile and the Ministry of Infrastructure.

Mexico - Edinburgh organised and ran a Wave and Tidal Energy R&D Scoping workshop with academics from all over Mexico, hosted by the National Autonomous University of Mexico (UNAM) in Mexico City and had meetings with UNAM, Conacyt and MOE to cement UK partnership in the establishment of the Mexican Innovation Centre in Ocean Energy (CEMIE Océano) just being set up in Mexico. Most recently UKCMER staff have been retained to lead the development of the Mexican Ocean Energy R&D Roadmap.

Canada – Strathclyde has an active research collaboration with Dalhousie University, Nova Scotia, focusing on the development of passive tidal rotor power regulation and control blade technologies for typical and higher energetic tidal environments. This has included collaborative laboratory testing of different blade geometries and composition over the past year. Queens has been working with the University of Victoria to propose a project considering the extreme loading of pitching flap-type WECs.

Taiwan - Edinburgh was again supported by NTOU to present the UKCMER Short Course on Numerical Hydrodynamic Modelling for Ocean Energy Converters in Keelung, Taiwan.

China – With EPSRC support UKCMER partners ran a proposal sandpit that led to collaboration between early career researchers in several UKCMER universities and: North-East Normal University; South China Institute of Oceanology, Dalian University of Technology; Hohai University, Ocean University of China, National Ocean Technology Center (NOTC) and the South China Sea Institute of Oceanology and Harbin University. This also led to the secondment to Edinburgh for one year of staff from the NOTC.

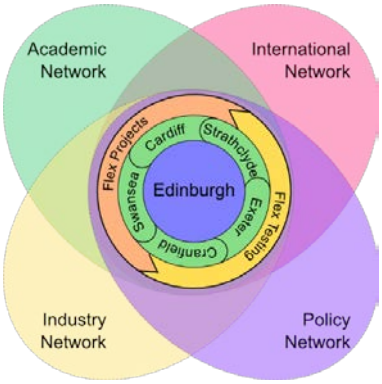
Korea - Strathclyde has an on-going research collaboration in tidal energy rotor blade and drive-train loadings with Inha University, South Korea. This includes staff and researcher exchange within a bi-lateral Korea to UK and UK to Korea exchange program undertaken in the past year.

Singapore – Strathclyde has a research collaboration in tidal energy array energy extraction performance optimisation with Nanyang Technological University (NTU). They also collaborate with the National University of Singapore on tribo-corrosion testing.

USA – Work on field measurements of flow patterns and turbulence intensity has involved collaboration with the Northwest National Marine Renewable Energy Centre (NNMREC) and the University of Washington. Researchers from NNMREC were co-authors on an award winning flow measurement paper. Sandia National laboratory is a partner in the DTOcean project as a result of links developed through UKCMER. Bangor and Cardiff have collaborated with University of Rhode Island and Mississippi State University have being working on wave/current interaction and the modelling of tidal turbine wakes.

5 Supergen Marine Phase 4

The existing hub of UKCMER was renewed in phase 4 under award EP/P008682/1 in October 2016, with the structure shown. Responsibilities within the core universities are:



Wallace	PI	Executive Director, Financial Management	
Ingram	CI	WP4 Research Director	
Jeffrey	CI	Network and Impact Manager	
Masters	CI	WP1	Tidal lead, Wales and Ireland liaison
Brennan	CI	WP5	Offshore wind lead, England liaison
Johanning	CI	WP2	Wave lead, PRIMare liaison
Johnstone	CI	WP3	Environment lead, Scotland liaison

The four GC projects in section 2 are integrated within the hub.

A Research Advisory Board includes: Dr G Connor (Nova Innovation); Dr R Yemm (Quoceant); Dr I Marti (ORE Catapult); C Bittencourt (DNV GL); S Bradley (ETI); Prof B Wilson (SAMS); Ing Dr J Bard (IWES Fraunhofer), A Mortimer (Sgurr Energy) and Prof A Lewis (MAREI). There are agreed and adopted R&D, technology and deployment roadmaps, produced and maintained by staff of UKCMER in Phase 3. 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.

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. Phase 4 of UKCMER will continue to:

- Conduct world-class fundamental and applied research that assists the wave, tidal and offshore wind energy sectors to accelerate deployment and ensure growth in generating capacity towards 2030 and 2050 targets;
- Train the next generation of UK, European and international researchers, industry graduates and policy makers;
- Expand and operate an inclusive marine network of academic researchers, industry and policy partners and international collaborators;
- Provide the highest quality of policy engagement and knowledge transfer.

5.2 Research Programme

There are significant common needs for fundamental to applied research spanning wave, tidal, offshore wind and, now, floating offshore wind energy technologies:

- Analysis and performance prediction of fully coupled hydro- aero- and electro-dynamic devices;
- Fluid:structure interaction;
- Cost effective manufacture, installation, operation and maintenance;
- Survival of extreme and fatigue loadings;
- Environmental and economic viability.

The phase 4 programme at the time of writing is just beginning and aims to address these needs in five interacting collaborative work packages.

WP1 Control and Performance

This will couple the Edinburgh electromechanical TCCS model to Swansea's unsteady GAD model and extend it to develop a fully bi-directional transient tide-to-wire model. The combined model will be

applied to both single machines and embedded in computational fluid dynamics codes to investigate array interactions. This will allow investigation and mitigation, through control, of the impact of turbulent flows and wakes on energy yield and loadings within the tidal array and also of the effect of network faults on the hydrodynamic response of TCCs.

Model results for a single turbine will be compared with those from experiments to be conducted under the Edinburgh FlowTurb GC Project *Response of Tidal Energy Converters to Combined Tidal Flow, Waves, and Turbulence* and those from Phase 3+. The research in FlowTurb will investigate the combined effect of tidal currents, gravity waves, and ambient flow turbulence on the dynamic response of tidal energy converters. A high quality database will be established comprising field-scale measurements from the Pentland Firth, Orkney waters, and Shetland region, supplemented by laboratory-scale measurements from Edinburgh University's FloWave wave-current facility. Controlled experiments will be carried out at Edinburgh University's FloWave facility to determine hydrodynamic loads on a tidal current device and hence parameterise wave-current-turbulence-induced fatigue loading on the turbine's rotor and foundation. This project aims to provide an enhanced understanding of tidal current-wave-turbulent flow interactions and their impact on the performance of tidal power devices. The dataset acquired within the project will be made widely available for academic and industry use, enabling further advances to take place in marine energy research. Collaborators include: Cape Breton University; DNV GL (UK); Marine Scotland Science; MASTS; National Institute of Ocean Tech (NIOT) Chennai; Nova Innovation Ltd; Partrac Ltd and Scotrenewables Tidal Power Ltd.

WP2 Risk and Reliability

WP2 will explore applicability and transfer of novel design and test processes, as practiced in other sectors like aviation and transport. Risk-based design is a move away from traditional deterministic iterative engineering design by combining risk-based and probabilistic reliability methods and mathematical modelling techniques into the design processes to optimise the cost and reliability.

Statistical design of test regimes will enable the performance and durability testing of individual sub-systems customarily replicates and accelerates in-situ load conditions. The Design of Experiments Method will be used to identify, select and schedule the combinations of governing factors to achieve most representative results in accelerated testing.

Test results will be compared with those from experiments to be conducted under the Cardiff DyLoTTA GC Project *Dynamic Loading of Turbines in a Tidal Array*. DyLoTTA aims to quantify the impact of wave-current interaction on the performance and integrity of tidal turbines when sited in an array and develop operational procedures to mitigate the impacts of these extreme loading patterns. Specifically the dynamic loading patterns on the blade, blade root and eccentricity induced within the drive train of array based turbines will be addressed and steps to measure and mitigate such effects will be defined. Industrial collaborators include: Ansys; Arup; Bosch Rexroth; National Instruments; Nautricity Ltd; Tidal Energy Ltd; Airborne Composites; ORE Catapult; Lloyds Register; SKF; Intertek; Mississippi State University; Dalhousie University Canada and Inha University from South Korea.

WP3 Extreme loads and survivability

Extreme responses in limiting operational and survival conditions used in "traditional" ship and on- off-shore structure design. WP3 aims to identify and transfer state-of-practice design tools and state-of-the-art analysis tools to predict extreme responses of wind, wave and tidal devices. The objectives are to: identify a set of benchmark extreme load scenarios; predict extreme responses in these cases using state-of-practice design tools; characterise extreme responses for these scenarios via model testing and examine the ability of hi-fidelity analysis tools to predict these extreme behaviours.

Model results will be compared with those from experiments conducted under the Swansea *Survivability of Floating Tidal Energy Converters (SURFTEC)* GC Project. It aims to provide a holistic vision for design optimisation to ensure reliability and survivability for floating tidal energy converters (FTECs). Computational modelling and real sea deployment measurements will enable the development of a tool that can be used to inform the optimum operational strategy and maximise survivability and reliability for

FTEC devices and arrays. There are three industrial partners associated with the project – the European Marine Energy Centre (EMEC), Oceanflow Energy, and Black and Veatch. The project partners will have an input on the decision about which of the measurable parameters on a FTEC are most important for monitoring and predicting loads, the survivability of the device, and its reliable operation. Data to enable the numerical model to be tested over a range of environmental conditions will be provided by EMEC. Black and Veatch will be closely involved in the development of the operational strategy and design guidance document, particularly in providing data to relate fatigue damage to component costs and LCoE.

WP4 Array Interaction

WP4 will develop new understanding in the modelling of dynamic flow conditions within tidal streams and of the nature of wave-current flow interactions penetrating down the water column and their influence on tidal velocities. This will be expanded to investigate the impact on tidal array performance and resulting energy yields. The GAD CFD and Unsteady, Wave-Coupled BEMT tools above will be evolved and verified for their application in tidal array performance assessment, to inform spatial planning in dynamic real-sea tidal flows to maximise energy yield. Model results for an array of three turbines will be compared with those from experiments to be conducted from Phase 3+, under the FlowTurb GC Project.

WP5 Materials and Structural Integrity

To move on from first generation concepts and practices and to help achieve cost competitive ORE structures and structural components, WP5 will critically review materials and fabrication methods currently used in Offshore Renewable Energy, explore contemporary materials used in other applications (nuclear, aerospace, shipping etc.,) and their ability to resist service stresses and more accurately and reliably define the loading regimes and structural dynamic responses giving rise to local stresses and develop new analytical methods to assess structural integrity taking account of the fluid:structure interaction and mooring dynamics integrated with device motion to determine whole structure response and loads. The work in WP5 will be aligned with the ambitions and activities of the GC Project *All Electric Drive Train for Marine Energy Converters (EDRIVE-MEC)* at Edinburgh.

Conversion of energy from wave action into electricity is ideally performed by a PTO and power conditioning system that can convert motion in multiple directions, react large forces or torques whilst operating at low velocity, variable voltage and frequency, with high reliability, availability and efficiency over a wide range of loads. EDRIVE aims to develop an integrated electrical power take off system with non-mechanical speed enhancement, integrated and reliable flexible power electronics, providing adaptive control over a range of operating regimes, taking into account nominal and extreme load conditions. Collaborators include: TU Delft; University de Chile; Albatern (UK), Carnegie Wave Power (AUS/UK) and Columbia Power Technologies (US), all of which have deployed devices at sea; Tecnalia (Spain) and electrical power developer Turbo Power Systems (UK).

Appendices

Appendix 1 Staff and Students of Supergen Phase 3

Core Academic and Admin Staff
Prof. A. R. Wallace – University of Edinburgh
Prof. D. M. Ingram - Edinburgh
Mr. H. Jeffrey – Edinburgh
Dr. L. Johanning – University of Exeter
Mr. C. Johnstone – University of Strathclyde
Prof. T. Whittaker – Queens University Belfast
Prof. J. Side* – Heriot-Watt University
Prof. I. Masters – Swansea University
Dr. G. Aggidis – Lancaster University
Prof. P. Stansby* – University of Manchester
Prof. A. Bahaj – University of Southampton
Prof. G. Houlsby – University of Oxford
Prof D. Greaves – Plymouth University
Ms. Pauline Clark – Edinburgh
* Also GC PI

Core Research Staff
Dr. G. Payne – Edinburgh
Dr. D. Forehand – Edinburgh
Dr A. Nambiar - Edinburgh
Dr. M. Topper – Edinburgh
Dr. P Thies – Exeter
Dr. M. Ibrahim – Strathclyde
Dr. K. Porter - Strathclyde
Dr. K. Gracie – Strathclyde
Dr. T. McCoombes – Strathclyde
Dr. S. Ordonez-Sanchez - Strathclyde
Dr. M. Folley – Queens
Dr. L. Kregting – Queens
Dr. P. Lamont-Kane - Queens

Doctoral Students
Tessa Gordelier - Exeter
Edward Ransley - Plymouth
David Crooks – Queens
Alex Olczak - Manchester
Katie Gracie – Strathclyde
Thomas Nevalainen – Strathclyde
Jose Barajas-Solano - Edinburgh
Susannah Cooke - Oxford
Andrew Want - Heriot-Watt
Thomas Lake – Swansea
Daniel Richardson - Lancaster
Daniel Coles - Southampton
Anna Garcia-Teruel – Edinburgh
Maria Pafi -Queens

GC Academic Staff (PIs only)
Dr. M. Mueller - Edinburgh
Dr. V. Venugopal - Edinburgh
Prof. C. Swan – Imperial
Prof. P. Taylor – Oxford
Prof. R. Miller - Cambridge
Prof. P. Dong – Dundee
Prof. M. Stack – Strathclyde
Prof. T. O'Doherty – Cardiff
Prof. M Belmont – Exeter
Dr. B. Elsassaer - Queens

GC Research Staff
Dr. M. Behera – Edinburgh
Dr R. Nemalidinne – Edinburgh
Dr T. Yung Zhi - Edinburgh
Dr. A. Young – Cambridge
Dr. Z. Ma - Manchester Metropolitan
Dr. J Spinneken - Imperial
Dr. M Latheef – Imperial
Dr. M. Hann – Plymouth
Dr. A. Kurniawan – Plymouth
Dr. R. MacIver – Heriot-Watt
Dr. S. Baston – Heriot-Watt
Dr. M. Bell – Heriot-Watt
Dr. H. Santo – Oxford
Dr. L. Chen – Bath
Dr. L. Sun - Bath
Dr. D. Stagonis – UCL
Dr. T. Feng - Manchester
Dr. S. Rolfo - Manchester
Dr. S. Longshaw - Manchester
Dr. U. Ahmed - Manchester
Dr. H. Gu - Manchester
Dr. E. Moreno - Manchester

Appendix 2 Publications by theme

The outputs in Phase 3 of Supergen, produced from Core and Grand Challenge research are listed by theme, as follows.

Arrays and Farms

1. ABANADES, J., GREAVES, D. & IGLESIAS, G.: "Wave farm impact on the modal state of a beach", Marine Geology, vol. 361, pp. 126–135, 01-Mar-15

The extraction of wave energy by the Wave Energy Converters (WECs) forming a wave farm results in a milder wave climate in its lee, which can have an impact on coastal processes. The objective of this work is to determine whether the beach morphology can be altered by the operation of the wave farm, and if so, to quantify this alteration. For this purpose, we examine how the farm affects the modal state of the beach with reference to a baseline (no farm) scenario. The modal state is defined based on an empirical classification that accounts for wave conditions, tidal regime and sediment size. As a beach typically goes through different modal states, we determine the percentages of time in an average year corresponding to each state in the baseline scenario, and how these percentages are altered by a wave farm as a function of its distance from the coast. This methodology is illustrated through a case study: Perranporth Beach (UK), an area of great potential for wave energy development. High-resolution numerical modelling is used, with two levels of grid refinement. We find that the wave farm has a relevant impact on the modal state of the system, which passes from wave-dominated to tide-dominated during significant periods of time. The sensitivity analysis, involving three cases with the farm at distances of 2 km, 4 km and 6 km from the beach, showed that the farm-to-coast distance plays a major role. Thus, the shift from a wave- to a tide-dominated beach is exacerbated in the case of the wave farm closest to the coastline, with the submarine bar vanishing over long periods of time. We conclude that the presence of the wave farm drastically alters the morphological response of the beach, and that this alteration is strongly dependent on the farm-to-coast distance.

2. AGGIDIS, G.A.: "Ocean Energy Research and State of the Art.", *International THRUST 2015, Thessaloniki, Greece*, May-15

Ocean energy has an essential role to play in response to increasing energy needs and CO2 reduction. It is safe, inexhaustible and mostly predictable, offering security of supply, innovation and economic development. Wave & Tidal energy offers a predictable and consistent source of renewable energy (DECC 2015). Developing the potential of marine energy resources will help the UK: a) save ~ 61 Mt of CO2 by 2025 - valued at an estimated £1.1 billion to the UK economy b) help meet the UK's renewable energy objectives. Wave and tidal stream energy has the potential to meet up to 20% of the UK's current electricity demand, representing a 30-to-50 GW installed capacity. Between 200 - 300 MWs of generation capacity may be able to be deployed by 2020, and at the higher end of the range, up to 27 GWs by 2050 (DECC RE Roadmap). The UK is at the forefront of the ocean renewable energy industry, through its research and development programmes, test facilities, and offshore experience from oil and gas extraction. The industry is still in its early stages however, and further research is needed to determine how best to exploit these assets.

3. AGGIDIS, G.A.: "Tidal Energy & Technology Current Trends.", *NTUA Flow 2014, Athens, Greece*, 12-13 Dec 2014

This paper provides an introduction to Tidal Energy and its Technological Current Trends. Examines the available resource both in the UK and globally for tidal current and tidal range opportunities. Highlights the technological State of the art with references for both tidal current and tidal range applications. Provides an update on the progress of the various tidal current and tidal range Projects globally. Mentions both the drivers and the barriers for progressing tidal energy forward and ten draws some conclusions.

4. ASHTON, I., VAN-NIEUWKOOP-MCCALL, J.C.C, SMITH, H.C.M. & JOHANNING, L.: "Spatial variability of waves within a marine energy site using in-situ measurements and a high resolution spectral wave model", *Energy*, *vol. 66*, pp. 699-710, DOI: 10.1016/j.energy.2013.12.065, 01-Mar-14

A high resolution spectral wave model is used to quantify the spatial wave climate on geographical scales relevant to intra-site variability for marine renewable energy installations. For the first time, results are compared to in-situ data from an array of four floating wave buoys, and demonstrate the ability of the spectral wave model SWAN

(Simulating WAves Nearshore) to resolve spatial differences in the wave climate. Examination of the model source terms highlights bottom friction and refraction as the primary processes contributing to the observed differences across the site. Wave models for climate assessments for marine renewable energy are not commonly operated at sufficient spatial resolution to accurately resolve intra-site variability. This study demonstrates that high spatial resolution spectral wave models, nested into a larger model domain, have the potential to provide an accurate and detailed prediction of the spatial variability of wave conditions across a marine renewable energy site. As such, they could be implemented to provide a more accurate resource assessment for wave energy array deployments, but also for engineering assessments of other marine energy technologies.

5. BAHAJ, A.S. & MYERS, L.E.: "Shaping array design of marine current energy converters through scaled experimental analysis", *Energy*, *vol. 59*, pp. 83-94, DOI: 10.1016/j.energy.2013.07.023, 15-Sep-13
Marine current energy converters or tidal turbines represent an emerging renewable energy technology that can provide a predictable supply of electricity. Single devices are in operation around the world with aspirations to deploy farms or arrays of multiple devices. We present an experimental study that has characterised the downstream wake flow around a 1/15th-scale turbine in a large circulating water channel and a series of experiments involving static actuator disks at 1/120th-scale allowing simulation of multiple-device layouts. Our analysis demonstrates that the near wake is highly turbulent with structures generated by the rotor and support structure. This region of flow may prove difficult to numerically simulate with a high degree of accuracy. In the far wake the performance of static actuator disks can be matched to mechanical rotors reducing scale and cost facilitating replication of complex array geometries. Here the ambient turbulence and geometric properties of the device/channel drive the wake recovery towards free stream conditions. Devices operating downstream of others will be subject to a non-steady flow field making comparative performance difficult. We discuss the possibility of unequal device specification and rated power within an array (unlike wind farms) providing a more representative measure of array performance.

6. BARBOUR, E., WILSON, I.A.G., BRYDEN, I.G., MCGREGOW, P.G., MULHERAN, P.A. & HALL, P.J.: "Towards an objective method to compare energy storage technologies: development and validation of a model to determine the upper boundary of revenue available from electrical price arbitrage", *Energy and Environmental Science*, *issue. 1*, DOI: 10.1039/C2EE02419E, 2012
This article proposes a methodology to calculate the upper boundary of the revenue available from the storage and time-shifting of electrical energy. The inputs to the mathematical model are a discrete time-series of the market index prices over a particular period of interest, and also specific energy storage device parameters. By using a Monte Carlo based optimisation method, the upper boundary of the revenue from time-shifting energy is determined. The method is explained and validated by showing that it finds the optimum solution that is the upper boundary for time-shifting revenue. In other words, a storage operator could never derive more revenue than this value from time-shifting alone and calculating this upper-boundary gives a reference value to compare the efficacy of other methods of estimation. The user defined storage device parameters include: fixed efficiencies for charging and discharging (%), the maximum capacity of the storage device (kWh), the charging and discharging power limits (kW), and the inclusion of an additional time-dependent efficiency that models the self-discharge of storage devices (% loss per hour). The combination of these parameters enables this method to give an objective comparison between different storage devices in terms of maximum arbitrage revenue. The output of the model provides not only a single value of the upper boundary revenue, but also the corresponding charging/discharging schedule.

7. BLACKMORE, T. & BAHAJ, A.S.: "Turbulence and its effect on the thrust and wake of a porous disc rotor simulator", *2nd Asian Wave and Tidal Energy Conference, Japan*, 28 July - 1 Aug 2014
Marine current turbines are still in their infancy with many devices at the development stage. Studies are often carried out using small scale laboratory experiments in flumes, towing tanks and numerical simulations to investigate the wakes and performance of scale marine current turbines. However, the characteristics of the inflow turbulence used in such studies is often not fully considered. Tidal flows are highly turbulent with a broad range of eddy sizes and intensities. So differences are expected when predictions of array energy yields are made from towing tanks studies with zero turbulence. This work considers the effects of turbulent eddy size on the thrust and wake behind a porous disc rotor simulator commonly used to represent marine current turbines in small scale experiments. The results show an increase in thrust coefficient with increasing length scale and a corresponding reduction in velocity deficit in the wake. These findings have implications to array special planning and hence energy yields.

8. BLACKMORE, T., BATTEN, W.M.J. & BAHAJ, A.S.: "Influence of turbulence on the wake of a marine current turbine simulator", *Proceedings of the Royal Society A*, DOI: 10.1098/rspa.2014.0331, 27-Aug-14
Marine current turbine commercial prototypes have now been deployed and arrays of multiple turbines under design. The tidal flows in which they operate are highly turbulent, but the characteristics of the inflow turbulence

have not being considered in present design methods. This work considers the effects of inflow turbulence on the wake behind an actuator disc representation of a marine current turbine. Different turbulence intensities and integral length scales were generated in a large eddy simulation using a gridInlet, which produces turbulence from a grid pattern on the inlet boundary. The results highlight the significance of turbulence on the wake profile, with a different flow regime occurring for the zero turbulence case. Increasing the turbulence intensity reduced the velocity deficit and shifted the maximum deficit closer to the turbine. Increasing the integral length scale increased the velocity deficit close to the turbine due to an increased production of turbulent energy. However, the wake recovery was increased due to the higher rate of turbulent mixing causing the wake to expand. The implication of this work is that marine current turbine arrays could be further optimized, increasing the energy yield of the array when the site-specific turbulence characteristics are considered.

9. BOUFERROUK, A., SAULNIER, J.B., SMITH, G.H. & JOHANNING, L.: "Field measurements of surface waves using a 5-beam ADCP", *Ocean Engineering*, *vol. 112*, pp. 173–184, DOI: 10.1016/j.oceaneng.2015.12.025, 15-Jan-16
This study examines the performance of an improved 5-beam ADCP, with a vertical beam, when deployed to measure non-directional waves in waters of 40 m depth. To assess the performance, the ADCP is compared with four co-located directional wave buoys. The surface elevation spectra as measured by the vertical beam compare well with estimates from the buoys in the range 0.10–0.35 Hz. Except for peak period, spectral estimates of wave height, mean energy period and spectral bandwidth from the vertical beam agree well with estimates from the buoys, showing only small differences of 2–7%. Some cases exist where either the ADCP or the buoys can resolve particular wave systems that the other sensor cannot resolve, though some of these instances may be the result of numerical artefact. At low frequencies, the ADCP shows a better sensitivity to swell components, and though the buoys can produce low frequency peaks, the difference between the two sensors is particularly evident during low energy sea states. At high frequencies, both sensors may show susceptibility to noise. The study intends to increase the level of confidence in using a 5-beam ADCP with a vertical beam, and of its comparative performance with a different wave sensor.

10. BRYDEN, I.G.: "Tidal Energy", *Encyclopedia of Sustainability Science and Technology*, 2011
Tidal energy, as interpreted in this essay, is considered to be the artificial extraction of energy from: either the rise or fall of the sea surface under the influence of tides or the extraction of energy from tidally driven currents. The associated theoretical energy resources are considerable on a global scale, but the geographic conditions necessary for significant tidal ranges, or current velocities, do tend to be restricted to a relatively small number of sites worldwide. Some of the most attractive tidal range sites, however, such as the Severn Estuary, between England and Wales, and the Bay of Fundy in Canada possess very considerable energy flux densities. Similarly, the most energetic tidal currents, such as in the Pentland Firth, to the north of the Scottish mainland, would also appear to offer major prospects for development. Although there has been considerable progress in recent years toward the commercial exploitation of the tides for energy, the use of tidal energy is not new. Tide “mills” were used in northern France and southern England as far back as the late Roman era but were most prolific during medieval times. Tidal waters turned water wheels to drive cereal grinding apparatus in areas with few rapidly flowing rivers. The Eling Tide Mill, for example, is still operational, largely as an educational and tourist facility, and is a very early example of tidal entrainment, represented by a barrage positioned to interfere with natural tidal flows. Entrainment is a more general term than “barrage” and encompasses alternative techniques such as lagoons. In the twentieth and twenty-first centuries, tides have been seriously re-examined as sources of energy to power industry and commerce.

11. COLES, D.S., BLUNDEN, L.S. & BAHAJ, A.S.: "Experimental testing for spatially averaged numerical modelling of large marine current energy converter arrays", *Grand Renewable Energy 2014 Proceedings*, 28 July - 1 Aug 2014
Experimental validation is required to understand the accuracy of 2D numerical modelling techniques for estimating the energy yield from large marine current converter (MCEC) arrays. A brief explaination of two commonly used methods is given along with a summary of their advantages/ limitations. Initial results are presented from experiments conducted in a recirculating flume using ten porous fences to simulate the wake effects of tidal turbines inside a large array. Results show good agreement with the flow behaviour inside large wind turbine arrays, where a balance between the shear from above that drives the flow and the drag from the turbine devices and the ground gives rise to a quasi-steady flow velocity behaviour inside the array.

12. COLLIN, A.J., NAMBIAR, A.J., KIPRAKIS, A.E., REA, J. & WHITBY, B.: "Network design tool for the optimal design of offshore ocean energy array networks.", *PowerTech conference, Eindhoven, Netherlands*, 29 June - 2 July 2015
This paper presents a simulation tool for the design and analysis of offshore ocean energy array networks. The tool integrates a number of modules which are divided into two core functions: the automation of the cable laying algorithm and subsequent creation of the network model, and the other performing the power flow analysis. The

results of the power flow analysis are used to inform the user of the levelised cost of energy of different network configurations. The tool is compatible with geographical information system (GIS) software to allow for easy integration within the array development, installation and operation and maintenance stages.

13. COOKE, S.C., WILLDEN, R.H.J, BYRNE, B.W., STALLARD, T. & OLCZAK, A.: "Experimental Investigation of Thrust and Power on a Partial Fence Array of Tidal Turbines.", *EWTEC Conference, Nantes, France*, 7-10 Sep 2015
An experimental investigation has been carried out into the flow around an array of eight porous discs simulating a partial fence array of tidal turbines in a channel. Thrust on each individual disc was measured, and this was combined with measured flow speeds to produce an indicative 'inferred power' removed from the flow by the discs. Results show similar thrust and power behaviour to that expected from partial fence theory, with a peak power achievable through careful selection of local blockage and device characteristics. However, end effects are shown to significantly reduce the extractable power from that predicted by theory, and parameter choice for peak power extraction may be more complex than theory suggests.

14. COOKE, S.C., WILLDEN, R.H.J., BYRNE, B.W., STALLARD, T. & FENG, T.: "An Experimental Investigation of Blockage in a Short Fence Array of Tidal Turbines.", *International Conference on Renewable Energies Offshore, Lisbon, Portugal*, DOI: 10.1201/b18973-83, 24-26 November 2014
The impact of array-scale blockage effects on the total power extractable from tidal turbine arrays has been the subject of much recent investigation. This paper summarises the results of a series of physical experiments on short fences of five porous discs to investigate blockage effects in the case of a long cross-stream fence array partially occupying the width of the channel. Disc thrusts are seen to increase as the width of the fence is reduced, which concurs with trends predicted by partial fence theory, although the magnitude of the thrust recorded is less than predicted by theory. Flow wake measurements display a degree of scale separation between device and array wake mixing.

15. CULLEY, D.M., FUNKE, S.W., KRAMER, S.C. & PIGGOTT, M.D.: "Integration of cost modelling within the micro-siting design optimisation of tidal turbine arrays", *Renewable Energy*, pp. 215-227, DOI: 10.1016/j.renene.2015.06.013, Jan-16
The location of individual turbines within a tidal current turbine array – micro-siting – can have a significant impact on the power that the array may extract from the flow. Due to the infancy of the industry and the challenges of exploiting the resource, the economic costs of realising industrial scale tidal current energy projects are significant and should be considered as one of the key drivers of array design. This paper proposes a framework for the automated design of tidal current turbine arrays in which costs over the lifespan of the array may be modelled and considered as part of the design optimisation process. To demonstrate this approach, the cost of sub-sea cabling is incorporated by implementing a cable-routing algorithm alongside an existing gradient-based array optimisation algorithm. Three idealised test scenarios are used to demonstrate the effects of a financial-return optimising design approach as contrasted with a power maximisation approach.

16. DALY, T., MYERS, L.E. & BAHAJ, A.S.: "Modelling of the flow field surrounding tidal turbine arrays for varying positions in a channel", *Philosophical Transactions of the Royal Society Part A*, *vol. 371*, *issue. 1985*, DOI: 10.1098/rsta.2012.0246, 2013
The modelling of tidal turbines and the hydrodynamic effects of tidal power extraction represents a relatively new challenge in the field of computational fluid dynamics. Many different methods of defining flow and boundary conditions have been postulated and examined to determine how accurately they replicate the many parameters associated with tidal power extraction. This paper outlines the results of numerical modelling analysis carried out to investigate different methods of defining the inflow velocity boundary condition. This work is part of a wider research programme investigating flow effects in tidal turbine arrays. Results of this numerical analysis were benchmarked against previous experimental work conducted at the University of Southampton Chilworth hydraulics laboratory. Results show significant differences between certain methods of defining inflow velocities. However, certain methods do show good correlation with experimental results. This correlation would appear to justify the use of these velocity inflow definition methods in future numerical modelling of the far-field flow effects of tidal turbine arrays.

17. DRAYCOTT, S., DAVEY, T., INGRAM, D.M., DAY, A. & JOHANNING, L.: "The SPAIR method: Isolating incident and reflected directional wave spectra in multidirectional wave basins", *Coastal Engineering*, *vol. 114*, pp. 265–283, DOI: 10.1016/j.coastaleng.2016.04.012, Aug-16
Wave tank tests aiming to reproduce realistic or site specific conditions will commonly involve using directionally spread, short-crested sea states. The measurement of these directional characteristics is required for the purposes of calibrating and validating the modelled sea state. Commonly used methods of directional spectrum reconstruction, based on directional spreading functions, have an inherent level of uncertainty associated with them. In this paper we aim to reduce the uncertainty in directional spectrum validation by introducing the SPAIR

(Single-summation PTPD Approach with In-line Reflections) method, in combination with a directional wave gauge array. A variety of wave conditions were generated in the FloWave Ocean Energy Research Facility, Edinburgh, UK, to obtain a range of sea state and reflection scenarios. The presented approach is found to provide improved estimates of directional spectra over standard methods, reducing the mean apparent directional deviation down to below 6% over the range of sea states. Additionally, the method isolates incident and reflected spectra in both the frequency and time domain, and can separate these wave systems over 360°. The accuracy of the method is shown to be only slightly sensitive to the level of in-line reflection present, but at present cannot deal with oblique reflections. The SPAIR method, as presented or with slight modification, will allow complex directional sea states to be validated more effectively, enabling multidirectional wave basins to simulate realistic wave scenarios with increased confidence.

18. EDMUNDS, M., MALKI, R., WILLIAMS, A.J., MASTERS, I. & CROFT, T.N.: “Aspects of Tidal Stream Turbine Modelling in the Natural Environment Using a Coupled BEM-CFD Model” *International Journal of Marine Energy, vol. 7,* pp. 20-42, ISSN 2214-1669, doi: 10.1016/j.ijome.2014.07.001., 2014
The problem of designing the optimal array of tidal stream turbines for the generation of marine renewable energy from the ocean, raises a number of questions about the distribution and layout of turbines in relation to the local bathymetry. The computational overhead of modelling such problems may be significant and costly. This paper aims to clarify the effects of particular phenomena associated with modelling tidal stream turbine arrays. To achieve this we use a RANS computational fluid dynamics model with an embedded blade element actuator disk to investigate various aspects of this problem, while maintaining reduced computational overhead. A study of axially aligned turbines, with each in the wake shadow of the previous turbine shows uniform effects for a 20 diameters downstream spacing, but more complex interaction for 10 diameters spacing. Investigation of the significance of inclusion of the nacelle and tower geometry in a CFD model shows that effects are negligible beyond six diameters downstream. An array of transverse contrarotating turbines are considered, where a device is placed close to and in the wake of a pair of upstream devices. Rotational direction has minimal effect on the power generated, but different turbulence is seen in the wake. Finally, marine currents around a headland are modelled and a single row fence of turbines is placed offshore from the headland at various blockage ratios. Power performance estimates and downstream wakes are created and they show increased power per device and improved total power production as the blockage ratio rises from 0.13 to 0.20. Additionally, the authors use stream surface techniques to visualise the flow which can give new insights to the physical processes observed.

19. EDWARDS, E.C., CRADDEN, L.C., INGRAM, D.M. & KALOGERI, C.: "Verification within wave resource assessments. Part 1: Statistical analysis"*, International Journal of Marine Energy*, *vol. 8*, pp. 70-83, DOI: 10.1016/j.ijome.2014.10.003, 2014
Interest in wave energy as a viable renewable energy has increased greatly in the past couple of decades. To determine the potential that a certain location has to harvest wave energy, a resource assessment must be performed for that location. As wave energy converter technologies get closer to market, it is becoming necessary to undertake more detailed resource assessments in order to determine the optimal location for deployment as well as the design and operating sea states. This study shows the level of sophistication that must be included in the verification process within a wave resource assessment. We describe the methodology in two articles. The first part shows how doing a complete statistical analysis of the fit of the model at the location of interest is essential for determining the reliability of the model data. Part 2 of this study will investigate the systematic trends of the fit of spectral values. In Part 1, it is shown that spatial analysis, the examination of distributions to reveal overall trends, and the careful choice of the appropriate statistical model to describe the fit of the wave model to buoy observations are all critical steps that must be added to verification processes. Part 2 demonstrates that looking closely at the fit of spectral values can reveal potentially vital issues for energy extraction. Better statistical validation gives the predictions of a particular resource assessment greater credibility or reveals areas where model accuracy must be improved.

20. FAIRLEY, I., EVANS, P., WOOLDRIDGE, C., WILLIS, M.R., & MASTERS, I.: "Evaluation of tidal stream resource in a potential array area via direct measurements", *Renewable Energy*, *vol. 57*, pp. 70-78, DOI: 10.1016/j.renene.2013.01.024, *ISSN: 0960-1481*, Sep-13
ADCP transects have used to characterise tidal stream resources in the Ramsey Sound area of Pembrokeshire, UK. Previous resource assessments have previously suggested that this area is one of the most promising for tidal stream deployments in the UK and this contribution confirms the commercial viability of the area. In this study three channels were considered: Ramsey Sound itself and two channels to the west formed by small offshore islands. Current velocities were used to compute the tidal energy flux through the channels. Maximum instantaneous peak flux through the three channels ranges from 180 MW to 70 MW. Flux cross-sections are presented and the impact of meso-scale bathymetric features on flux and on the cross-transect variation of maximum flux over the tidal cycle is described and discussed. Theoretical values of extractable power potential are

calculated and range between 7.2 MW and 21.8 MW. These values are approximately ¼ of the average flux through the measured cross-section. One channel is identified as being preferable for the first stage of array deployments given greatest homogeneity of flux through the channel cross-section and it having the highest power potential.

21. FAIRLEY, I., NEILL, S., WROBELOWSKI, T., WILLIS, M.R. & MASTERS, I.: "Potential array sites for tidal stream electricity generation off the Pembrokeshire coast", *EWTEC 2011, Southampton, UK*, 2011
This paper details a resource and constraint assessment for tidal stream deployment sites around Pembrokeshire, Wales. Based on a minimum peak spring current of 2ms-1 , seabed depth and gradient constraints, four sites, providing a total area of 48.3km2 were identified. Using the significant impact factor method, it is estimated that these sites could provide 1.3TWhrs per year. Constraints such as port proximity, fishing activity and SAC habitats were considered. It is suggested that the most promising area for first stage turbine array deployment is the Bishops and Clerks area.

22. FAIRLEY, I., WILLIS, M.R., & MASTERS, I.: "The potential future wave resource utilisation around Wales", *Coastal Management, Belfast, UK*, Nov-11
A GIS analysis is used to determine potential deployment areas for wave energy converters in Welsh waters. It is shown that there are substantial areas suitable for wave farm development. A numerical wave model, SWAN, is used as a tool to test the impact and viability of extracting Welsh Assembly Government (WAG) marine renewable energy targets from the GIS defined extraction areas. The effect of wave farms in English waters on Welsh resource is also tested. Wave farms in SW England could cause at most a 10% reduction in wave energy in Welsh deployment areas, but the prime deployment areas around Pembrokeshire would be largely unaffected. This paper suggests that there is a 1.6GW deployment capacity in Welsh waters. However, this magnitude of deployment is unlikely given competing demands on sea space. If it is possible to deploy wave devices of this capacity, under peak generation conditions then coastal reduction in wave height is likely to be noticeable. This may have effects on the south west Gower coast, exposed coasts between Tenby and Milford haven in Pembrokeshire and around Whitesands, based on the tested 1.6GW scenario. It is suggested that numerical modelling of wave resource is crucial to accurately predict technical and practical resources.

23. FAIRLEY, I., WILLIS, M., MASTERS, I. & REEVE, D.: "A consideration of the deployment of wave energy converters in Welsh waters based on resource and financial considerations", *Fourth International Conference on Ocean Energy (ICOE), Dublin, Ireland*, 17-19 Oct 2012
This work discusses the potential for wave energy deployment in Welsh waters based on available resource and site specific economics. Firstly, a resource analysis for three commercially leading wave energy converters (Wave Dragon, Pelamis, AquaBuoy) based on measurements at two locations is presented. Comparison is made with the wave climate at the Wavehub site, Cornwall. There is little difference between resource in Wales and in Cornwall. Secondly, to better define potential deployment areas in Wales consideration has been given to location dependant economics of wave energy converter deployment in Wales. Site related considerations include depth dependant mooring costs, operation costs based on distance from port, cable costs and constraint related consenting costs. GIS based representation of cost shows that in general cost increases with distance from land, primarily due to cable costs, but that constraint associated cost and bathymetry also have effects.

24. FINLAY, L., JEFFREY, H., MACGILLIVRAY, A. & AGGIDIS, G.A.: "Water: Ocean Energy and Hydro", *Global Energy: Issues, Potentials, and Policy Implications*, Sep-15
The first part of the chapter examines the wave and tidal stream sector, providing an overview of the wave and tidal resource both within the UK and globally, and provides details of the various classifications of wave and tidal energy device types. An outline of the current status of ocean energy array progress, and the development of future array projects, provides details of the technology challenges the sector faces. Details of the levelized costs of energy for wave and tidal energy, the need and potential for cost reduction within the sector, information regarding the uncertainty of cost within the sector, and an overview of the potential of cost of energy reduction through innovation are explored in detail. The second part of the chapter reviews the installed capacity, technology, and operation of hydropower, together with the prospects for its further development and possible social and environmental constraints on that development. It has long been acknowledged that the power of water can make a considerable contribution to energy generation around the world. There are a number of different forms of energy generation from both fresh and salt water, and this chapter aims to provide an overview of the energy sectors powered by both hydropower and the oceans. The chapter is split into two distinct sections; the ocean energy section provides an overview of ocean energy, including the associated resource, technology, technology and research challenges, costs, and policies relating to the sector. The hydropower section provides a review of the installed capacity and generation, technology and operations, future developments, and the social and environmental constraints.

25. FOLLEY, M. & WHITTAKER, T.: "Preliminary cross-validation of wave energy converter array interactions", *32nd International Conference on Ocean, Offshore and Arctic Engineering, Nantes, France*, DOI: 10.1115/OMAE2013-10837, 2013
The development of wave energy for utility-scale electricity production requires an understanding of how wave energy converters will interact with each other when part of a wave farm. Without this understanding it is difficult to calculate the energy yield from a wave farm and consequently the optimal wave farm layout and configuration cannot be determined. In addition, the uncertainty in a wave farm's energy yield will increase the cost of finance for the project, which ultimately increases the cost of energy.Numerical modelling of wave energy converter arrays, based on potential flow, has provided some initial indications of the strength of array interactions and optimal array configurations; however, there has been limited validation of these numerical models. Moreover, the cross-validation that has been completed has been for relatively small arrays of wave energy converters. To provide some validation for large array interactions wave basin testing of three different configurations of up to 24 wave energy converters has been completed. All tests used polychromatic (irregular) sea-states, with a range of long-crested and short-crested seas, to provide validation in realistic conditions.The physical model array interactions are compared to those predicted by a numerical model and the suitability of the numerical and physical models analysed. The results are analysed at three different levels and all provide support for the cross-validation of the two models. The differences between the physical and numerical model are also identified and the implications for improving the modelling discussed.

26. FOLLEY, M., BABARIT, A., O'BOYLE, L., CHILD, B., FOREHAND, D., SILVERTHORNE, K., SPINNEKEN, J., STRATIGAKI, V. & TROCH, P.: "A review of numerical modelling of wave energy converter arrays", *31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2012), Rio de Janeiro*, DOI: 10.1115/OMAE2012-83807, 1-6 July 2012
Large-scale commercial exploitation of wave energy is certain to require the deployment of wave energy converters (WECs) in arrays, creating 'WEC farms'. An understanding of the hydrodynamic interactions in such arrays is essential for determining optimum layouts of WECs, as well as calculating the area of ocean that the farms will require. It is equally important to consider the potential impact of wave farms on the local and distal wave climates and coastal processes; a poor understanding of the resulting environmental impact may hamper progress, as it would make planning consents more difficult to obtain. It is therefore clear that an understanding the interactions between WECs within a farm is vital for the continued development of the wave energy industry.To support WEC farm design, a range of different numerical models have been developed, with both wave phase-resolving and wave phase-averaging models now available. Phase-resolving methods are primarily based on potential flow models and include semi-analytical techniques, boundary element methods and methods involving the mild-slope equations. Phase-averaging methods are all based around spectral wave models, with supra-grid and sub-grid wave farm models available as alternative implementations.The aims, underlying principles, strengths, weaknesses and obtained results of the main numerical methods currently used for modelling wave energy converter arrays are described in this paper, using a common framework. This allows a qualitative comparative analysis of the different methods to be performed at the end of the paper. This includes consideration of the conditions under which the models may be applied, the output of the models and the relationship between array size and computational effort. Guidance for developers is also presented on the most suitable numerical method to use for given aspects of WEC farm design. For instance, certain models are more suitable for studying near-field effects, whilst others are preferable for investigating far-field effects of the WEC farms. Furthermore, the analysis presented in this paper identifies areas in which the numerical modelling of WEC arrays is relatively weak and thus highlights those in which future developments are required.

27. FOLLEY, M., CORNETT, A., HOLMES, B., LENEE-BLUHM, P. & LIRIA, P.: "Standardising resource assessment for wave energy converters", *Fourth International Conference on Ocean Energy (ICOE), Dublin, Ireland*, 17-19 Oct 2012
As the wave energy industry grows and begins to attract significant commercial investment, it is important that the industry begins to use generally accepted methods and procedures in order to increase industry and investor confidence. In response, the International Electrotechnical Commission (IEC) set up a Technical Committee charged with developing standards for the marine renewable energy sector (IEC/TC114). Subsequently, as one of its initial steps, the Committee created a project to develop a Technical Specification for the assessment and characterisation of wave energy resources. A Project Team including international experts from industry and academia with experience covering oceanography, engineering and wave energy technologies has been working towards this goal for the past two years. Although it is expected that this Technical Specification (TS) will continue to evolve as understanding of the wave energy resource and its relationship with Wave Energy Converters (WECs) develops, this paper details the main elements of the proposed wave energy Resource Assessment TS and explains the reasoning behind the specified methods and procedures. In addition, this TS's relationship with another TS

specifying methods for assessing the Power Performance of WECs is also explained and illustrated using an example.

28. FOLLEY, M., HENRY, A. & WHITTAKER, T.: "Contrasting the hydrodynamics of heaving and surging wave energy converters", *European Wave and Tidal Energy Conference. Nantes, France*, 7-10 Sep 2015
As wave energy conversion moves closer to becoming a commercially viable technology there is still no sign of convergence in the design space. The vast plethora of proposed Wave Energy Converter (WEC) concepts makes their classification and assessment a difficult task. While the machine design advantages of each concept may be assessed by a reputable third party, a misunderstanding of the fundamental hydrodynamics can lead to the overlooking, or indeed the overfunding, of a WEC concept. The classical oscillation mode for a WEC is heave, and much of the fundamental knowledge on wave energy conversion has been developed while analysing perhaps the simplest WEC, the heaving buoy. However, there are an increasing number of devices using surge as their primary mode of wave energy conversion. As little has been written about surging devices they are often treated in a similar manner to their heaving cousins which inevitably leads to some misperceptions regarding this device type. This paper seeks to make a clear distinction between the hydrodynamics of surging and heaving devices and by doing so demonstrates that the application of design principles developed for heaving WECs are often inappropriate for the design of surging WECs.

29. FOREHAND, D.I.M., KIPRAKIS, A.E., NAMBIAR, A.J. & WALLACE, A.R.: "A fully coupled wave-to-wire model of an array of wave energy converters", *IEEE Transactions on Sustainable Energy*, *vol. 7*, *issue. 1*, pp. 1-11, DOI: 10.1109/TSTE.2015.2476960, Jan-16
This paper describes a fully coupled, wave-to-wire time-domain model that can simulate the hydrodynamic, mechanical, and electrical response of an array of wave energy converters. Arrays of any configuration can be simulated to explore both the effects of the array on the electricity network and of network events on the devices within the array. State-space modeling of the hydrodynamic radiation forces enables fast and accurate prediction of the interacting response of multiple devices, including the effects of wave climate, control strategies, and network power flow. Case studies include the demonstration of the bidirectional interaction of the array and the network.

30. FUNKE, S.W., FARRELL, P.E. & PIGGOT, M.D.: "Tidal turbine array optimisation using the adjoint approach.", *Renewable Energy*, *vol. 63*, pp. 658-673, DOI: 10.1016/j.renene.2013.09.031, 2014
Oceanic tides have the potential to yield a vast amount of renewable energy. Tidal stream generators are one of the key technologies for extracting and harnessing this potential. In order to extract an economically useful amount of power, hundreds of tidal turbines must typically be deployed in an array. This naturally leads to the question of how these turbines should be configured to extract the maximum possible power: the positioning and the individual tuning of the turbines could significantly influence the extracted power, and hence is of major economic interest. However, manual optimisation is difficult due to legal site constraints, nonlinear interactions of the turbine wakes, and the cubic dependence of the power on the flow speed. The novel contribution of this paper is the formulation of this problem as an optimisation problem constrained by a physical model, which is then solved using an efficient gradient-based optimisation algorithm. In each optimisation iteration, a two-dimensional finite element shallow water model predicts the flow and the performance of the current array configuration. The gradient of the power extracted with respect to the turbine positions and their tuning parameters is then computed in a fraction of the time taken for a flow solution by solving the associated adjoint equations. These equations propagate causality backwards through the computation, from the power extracted back to the turbine positions and the tuning parameters. This yields the gradient at a cost almost independent of the number of turbines, which is crucial for any practical application. The utility of the approach is demonstrated by optimising turbine arrays in four idealised scenarios and a more realistic case with up to 256 turbines in the Inner Sound of the Pentland Firth, Scotland.

31. GARCIA-OLIVA, M., TABOR, G. & DJORDJEVIC, S.: "Modelling the impact of tidal farms on flood risk in the Solway Firth estuary", 2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR), University of the Highland and Islands, Stornoway, United Kingdom, 28 April - 2 May 2014
The available tidal energy resource within estuaries is quite significant in the UK but these areas are usually prone to flooding. The objective of this study is the assessment of flood risk due to tidal farms in estuaries through its application to a real case, the Solway Firth. A numerical model has been developed to represent the hydrodynamic conditions of the estuary during an extreme event. The results from this model for the maximum velocities indicate the suitable locations for the tidal farms. Two different cases with parallel and staggered configurations of tidal farms have been introduced. The comparison of the results for the maximum water levels between the situations with and without the farms allow us to draw conclusions about changes of flood risk due to the farm and contrast the impact of two different arrangements of turbines. The values of the energy extracted in both configurations will also be investigated.

32. GEBRESLASSIE, M.G, TABOR, G.R. & BELMONT, M.R.: "Investigation of the performance of a staggered configuration of tidal turbines using CFD", *Renewable Energy*, *vol. 80*, pp. 690-698, DOI: 10.1016/j.renene.2015.03.001, 2015
This paper investigates the influence of wake interaction and blockage on the performance of individual turbines in a staggered configuration in a tidal stream farm using the CFD based Immersed Body Force turbine modelling method. The inflow condition to each turbine is unknown in advance making it difficult to apply the correct loading to individual devices. In such cases, it is necessary to establish an appropriate range of operating points by varying the loading or body forces in order to understand the influence of wake interaction and blockage on the performance of the individual devices. The performance of the downstream turbines was heavily affected by the wake interaction from the upstream turbines, though there were accelerated regions within the farm which could be potentially used to increase the overall power extraction from the farm. Laterally closely packed turbines can improve the performance of those turbines due to the blockage effect, but this could also affect the performance of downstream turbines. Thus balancing both the effect of blockage and wake interaction continues to be a huge challenge for optimising the performance of devices in a tidal stream farm.

33. GEBRESLASSIE, M.G., BELMONT, M.R. & TABOR, G.R.: "Comparison of Analytical and CFD Modelling of the Wake Interactions of Tidal Turbines", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
The status of marine current tidal energy technology is currently in the research and development phase, with a few deployments and tests of prototypes under-way in some countries. There is huge pressure for tidal farms to be of GW scale in order to have a real, economically viable impact on renewable energy utilization targets outlined for 2020. A route to achieving this is the large scale energy farm philosophy, similar to wind farms, based on very large numbers of unit current tidal stream devices. However, this in-mature technology development raises different research questions which lead to further problems in the practical implementation of tidal stream devices. Thus, the aim of the work described in this paper was (i) to formulate simplified parameterised analytic models of individual and clusters of tidal stream devices using the concept of linear momentum actuator disc theory, (ii) to perform a detailed calculations of the flow field of multiple turbines using the developed models, and (iii) to compare the analytic model results with the results calculated using a CFD based Immersed Body Force (IBF) model. This study has been mainly focused on a new device, Momentum-ReversalLift (MRL), which is a cross flow type of tidal turbine developed by Aquascientific Ltd. Several analytic models have been developed to describe the flow characteristics downstream of the turbine, i.e. the wake velocity profile and to estimate the total power extraction from a tidal stream farm containing ideally tenth and hundreds of devices. The developed models showed the capability to examine the wake characteristics and to estimate the performance of clusters of turbines taking in to consideration the influence of turbine to turbine interactions. A small longitudinal spacing between turbines inflicted a massive energy shadowing that affects the performance of downstream turbines. Based on the analysis of the influence of wake interaction, more than 91% of the performance of an isolated turbine can be achieved with turbines spaced 20D apart. In addition, comparison of the wake velocity profiles and the power extraction calculated using both the analytic and CFD models showed reasonable agreement.

34. GEBRESLASSIE, M.G., TABOR, G.R. & BELMONT, M.R.: "Numerical simulation of a new type of cross flow tidal turbine using OpenFOAM - Part II: Investigation of turbine-to-turbine interaction", *Renewable Energy*, *vol. 50*, pp. 1005-1013, DOI: 10.1016/j.renene.2012.08.064, 2013
Prediction of turbine-to-turbine interaction represents a significant challenge in determining the optimized power output from a tidal stream farm, and this is an active research area. This paper presents a detailed work which examines the influence of surrounding turbines on the performance of a base case (isolated turbine). The study was conducted using a new CFD based, Immersed Body Force (IBF) model, which was validated in the first paper, and an open source CFD software package OpenFOAM was used for the simulations. The influence of the surrounding turbines was investigated using randomly chosen initial lateral and longitudinal spacing among the turbines. The initial spacing was then varied to obtain four configurations to examine the relative effect that positioning can have on the performance of the base turbine.

35. GEBRESLASSIE, M.G., TABOR, G.R. & BELMONT, M.R.: "CFD simulations for investigating the wake states of a new class of tidal turbine", *Journal of renewable energy and power quality (JRE&PQ)*, *vol. 10*, *issue. 241*, 2012
The interest of tidal energy exploitation is increasing in recent years promoting the need for development of efficient tidal turbines. This paper investigates the wake states of energy extraction by a new tidal turbine design, the Momentum Reversal Lift (MRL), developed by Aquascientific Ltd with a different method of tidal turbine modelling (body force) using an open source computational fluid dynamics (CFD) code, OpenFOAM. The body force CFD model results showed better turbulent patterns downstream of the turbine showing its quality compared to porous disc method which has been used for tidal turbine modelling. The simulations on a single MRL device showed that the wake recovers into 94% of the free stream at 20D downstream of the turbine. The performance of a downstream turbine simulated with 20D spacing was reduced by almost 7.17% due to the energy

shadowing created by the upstream wake. Thus, it is necessary to have at least 20D turbine spacing to maintain more than 92% of the performance of an isolated turbine.

36. GEBRESLASSIE, M.G., TABOR, G.R. & BELMONT, M.R.: "Simulations for Sensitivity Analysis of Different Parameters to the Wake Characteristics of Tidal Turbine", *Open Journal of Fluid Dynamics*, *vol. 2*, *issue. 3*, pp. 56-64, 2012
This paper investigates the sensitivity of width proximity and mesh grid size to the wake characteristics of Momentum Reversal Lift (MRL) turbine using a new computational fluid dynamics (CFD) based Immersed Body Force (IBF) model. This model has been added as a source term into the large eddy simulation (LES), which is developed for solving two phase fluids. The open source CFD code OpenFOAM was used for the simulations. The simulation results showed that the grid size and width proximity have had massive impact on the flow characteristics and the computational cost of the tidal turbine. A fine grid size and large width inflicted longer computational time. In contrast, a coarse grid size and small width reduced the computational time but showed poor description of the flow features. In addition, a close proximity of the domain's wall boundary to the turbine affected the free surface, the air body, and the flow characteristics at the interface between the two phases. These results showed that careful investigation of a suitable grid size and spacing between the wall boundary and the turbine is important to minimise the effect of these parameters on the simulation results.

37. GREENWOOD, C.E., CHRISTIE, D. & VENUGOPAL, V.: "The Simulation of Nearshore Wave Energy Converters and their Associated Impacts around the Outer Hebrides", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
The results of a numerical wave modelling study carried out to assess the nearshore effects of wave energy extraction on the local wave climate by an array of hypothetical wave energy converters (WECs) are presented in this paper. This study uses the Danish Hydraulic Institute's (DHI) MIKE 21 Spectral Wave model to identify and test three different techniques of simulating hypothetical WECs on a regional scale. The results suggest the more complex approach of simulating absorption using directional and frequency absorption spectra in addition to the effects of wave reflections yields a more realistic simulation. This technique was further applied to a potential wave energy deployment site consisting of an array of 30 WEC devices identified by the Crown Estate in the Outer Hebrides in the United Kingdom. The boundary input used seasonal averaged data to represent winter, summer and a complete year's wave spectra. The results suggest there is an average shoreline reduction in wave power behind the array of 5% with a peak value of 9.5%. The inclusion of wave reflection in to the model leads to a larger average percentage change in wave power of 7.5% 300m from the devices. While the results of this study also provide an insight into the distribution of wave energy around a nearshore array, this study focuses on developing advanced technique for the simulation of WECs.

38. HASHEMI, M.R., NEILL, S.P., ROBINS, P.E., LEWIS, M.J. & WARD, S.L.: "Recent developments in wave-current interaction and sediment impact studies at a planned tidal-stream array at the Skerries, UK", *1st International Conference on Renewable Energies Offshore, Lisbon, Portugal*, 24-26 November 2014
Marine Current Turbines (MCT)/ Siemens are planning to install a tidal stream array off the NW coast of Anglesey, a large island located off the NW coast of Wales, UK. This project might be the first tidal stream array in the UK, or possibly the world. In many locations of the NW European shelf seas, including this site, an energetic wave climate is present at sites suitable for the development of tidal-stream arrays. Wave-current interaction (WCI) processes can potentially alter tidal currents, and consequently affect the tidal stream resource at such sites. A high resolution coupled wave-tide model of the proposed tidal stream array to the NW of Anglesey has been developed using the unstructured FEM model TELEMAC/TOMAWAC. We investigated the effect of WCI processes on the tidal resource of the site for typical dominant wave scenarios of the region. To address this, a simplified method to include the effect of waves on bottom friction felt by the currents was implemented. The results showed that as a consequence of the combined effects of the wave radiation stresses and enhanced bottom friction, the tidal energy resource can be reduced by up to 20% and 15%, for extreme and mean winter wave scenarios, respectively. Whilst this study assessed the impact for a site that is relatively exposed to waves, the magnitude of this effect is variable, and is expected to be amplified in sites which are much more exposed to waves. Additionally, the impact of the tidal-stream array on bedload sediment transport is briefly discussed in this research. Since the extraction of tidal energy will generally reduce current speeds, it can alter the localised and far-field morphodynamics of the sea bed. For instance, sand banks which are formed by tidally generated eddy systems in the vicinity of headlands and islands are sensitive to small changes in tidal currents. A simplified analytical approach has been developed and implemented to assess the impact of tidal-stream arrays on bedload transport, which is considered as the main factor which controls seabed morphodynamics.

39. JEFFREY, H., WINSKEL, M. & JAY, B.: "Accelerating the development of marine energy: exploring the prospects, benefits and challenges", *Technological Forecasting and Social Change*, *vol. 80*, pp. 1306-1316, DOI: 10.1016/j.techfore.2012.03.004, 2013

Energy system scenarios and modelling exercises may under-represent the learning potential of emerging technologies such as marine energy. The research described here was devised to represent this potential, and thereby explore the possible role of marine energy in future energy systems. The paper describes a scenario for the accelerated development of marine energy technology, and the incorporation of this scenario into wider scenarios of UK energy system decarbonisation from now to 2050. The scenarios suggest that the accelerated development of marine energy could contribute significantly to the decarbonisation of energy supply in the UK, especially over the medium to long term. However, this is predicated on sustained innovation, learning and cost reduction over time. Encouragingly, a number of recently established policy support programmes are now beginning to stimulate the development of marine energy in Scotland, the UK and beyond. As the paper discusses, building on these initiatives, and 'realising' the accelerated development of marine energy, present a number of challenges, and will increasingly require international efforts. However, the potential rewards are very substantial.

40. JOHNSTONE, C.M., PRATT, D., CLARKE, J.A. & GRANT, A.D.: "A techno-economic analysis of tidal energy technology", *International Journal of Renewable Energy*, *vol. 49*, pp. 101-106, DOI: 10.1016/j.renene.2012.01.054, *ISSN: 0960-1481*, Jan 2-013
The choice of which type of electrical power generation technology to adopt is driven by a number of factors including: cost of generated electricity; responsiveness of generating plant to demand; security of supply/resource availability; environmental impact; and execution risk. Within these, tidal energy is unique as a renewable technology since it has the capability of providing predictable, firm power contributing to security of supply. This predictability gives tidal energy additional value in a future electricity market. Especially one where stochastic renewable technologies contribute to a sizable component of the power supplied; and where reserve capacity is required to maintain supply during periods of non-availability. In the shorter term, in order for tidal energy to gain commercial acceptance, tidal technologies under development need to produce electricity at a competitive price. This paper examines the drivers influencing electricity pricing; current tidal energy developments, aimed at reducing capital costs; and bench-mark these against offshore wind.

41. KEOGH, B., MYERS, L.E. & BAHAJ, A.S.: "Marine current turbine performance and wake evolution with changes in channel geometry", *Proceedings of Asian Wave and Tidal Energy Conference, Tokyo, Japan*, Aug-14
Marine current turbine technology and sea deployment are still in their infancy with some prototype commercial turbines currently being tested in sheltered sites and at test centres. Hence a lot of studies are being conducted at model laboratory scale in flumes and towing tanks. These are used to inform numerical simulations and planning for array deployment. In this work we provide the results of a small-scale experimental study which investigates the changes in tidal current turbine performance with changes in channel size and geometry. Static porous plates were used as turbine simulators in a circulating water flume at the University of Southampton's Chilworth facility. Changes in device performance were seen to vary with both changes in area blockage ratio and channel aspect ratio (channel depth/width ratio). Similarly wake changes were recorded, with axisymmetric wake profiles observed in channels where large disparities in depth and width were investigated. These results provide insight for the tidal community into some of the flow effects that may be encountered when installing tidal current energy conversion devices in arrays.

42. KRAMER, S., HILL, J., KREGTING, L., PIGGOTT, M. & ELSÄßER, B.: "The modelling of tidal turbine farms using multi-scale, unstructured mesh models", *2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR), University of the Highland and Islands, Stornoway, United Kingdom*, 28 April - 2 May 2014
A model inter comparison study is presented between MIKE 21 and Fluidity for the modelling of tidal turbine farms. Close agreement is observed in the outcomes of both models. An important aspect is the parameterisation of turbines in tidal models that typically do not re-solve the individual turbine scale. Here we present a correction to the applied drag force to ensure results that are less mesh resolution dependent.

43. LAMONT-KANE, P., FOLLEY, M. & WHITTAKER, T.: "Investigating Uncertainties in Physical Testing of Wave Energy Converter Arrays", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Much of the published literature focusing on the performance assessment of arrays of Wave Energy Converters describes work carried out in analytical and numerical domains. Physical validation of these results using a wave basin has been identified as an urgent requirement in the wave energy industry. Unfortunately, physical modelling of array interactions using a wave basin is challenging due to the difficulties in replicating numerical model characteristics. In particular, physical experiments and measurements may not be completely repeatable and reproducible. This uncertainty may impact validation of numerical models where it is of the same order of magnitude as the array interactions to be measured. This paper describes the primary uncertainties encountered in a set of physical array tests undertaken at Queen's University Belfast. The sources of uncertainty are described, along with statistical measures used to assess their impact and ensure that model data collected is of sufficient

quality to allow numerical validation. The paper concludes with a discussion summarising the findings and demonstrating the importance of understanding uncertainties, showing their potential effects on results obtained.

44. LI, G. & BELMONT, M.: "Model predictive control of an array of sea wave energy converters Part II: an array of devices", *Renewable Energy*, *vol. 68*, pp. 540-549, DOI: 10.1016/j.renene.2014.02.028, 2014
This paper addresses model predictive control (MPC) of highly-coupled clusters of sea wave energy converters (WECs). Since each WEC is not only a wave absorber but also a wave generator, the motion of each WEC can be affected by the waves generated by its adjacent WECs when they are close to each other. A distributed MPC strategy is developed to maximize the energy output of the whole array and guarantee the safe operation of all the WECs with a reasonable computational load. The system for an array is partitioned into subsystems and each subsystem is controlled by a local MPC controller. The local MPC controllers run cooperatively by transmitting information to each other. Within one sampling period, each MPC controller performs optimizations iteratively so that a global optimization for the whole array can be approximated. The computational burden for the whole array is also distributed to the local controllers. A numerical simulation demonstrates the efficacy of the proposed control strategy. For the WECs operating under constraints explored, it is found that the optimized power output is an increasing function of degree of WEC–WEC coupling. Increases in power of up to 20% were achieved using realistic ranges of parameters with respect to the uncoupled case.

45. LI, X., LI, M., CHEN, X. & THORNE, P.D.: "3D-CFD numerical modelling of large scale impacts of tidal turbine arrays using an oceanographic model.", *34th International conference on Coastal Engineering, ASCE, Seoul, Korea*, DOI: 10.9753/icce.v34.structures.31, 15-20 June 2014
It is still challenging to predict the effects of large scale tidal turbine arrays on its surrounding hydrodynamic environment and the sediment transport process, especially when a realistic method has yet to be fully developed for the representation of tidal stream device in the existing oceanographic models. Generally, the commonly used regional oceanographic models are developed for near-horizontal flows, which make them inappropriate to simulate the complex 3D flows around the tidal turbine structure directly. Therefore, the present study aims to develop a three-dimensional parameterization of a tidal turbine that can be used in a large scale oceanographic model, such as Finite-Volume, primitive equation Community Ocean Model (FVCOM). The additional retarding force method is extended in 3D flow conditions and applied in FVCOM to represent the tidal stream devices. Detailed laboratory measurements and computational fluid dynamics, CFD, calculated results are used to verify the model’s accuracy in prediction of hydrodynamics around the devices.

46. LV, X., ZOU, Q.P. & REEVE, D.E.: "Numerical simulation of overflow at weirs using an accurate hydrodynamic model", *Advances in Water Resources*, *vol. 34*, *issue. 10*, pp. 1320-1334, DOI: 10.1016/j.advwatres.2011.06.009, 2011
This paper presents the applications of a newly developed free surface flow model to the practical, while challenging overflow problems for weirs. Since the model takes advantage of the strengths of both the level set and volume of fluid methods and solves the Navier-Stokes equations on an unstructured mesh, it is capable of resolving the time evolution of very complex vortical motions, air entrainment and pressure variations due to violent deformations following overflow of the weir crest. In the present study, two different types of vertical weir, namely broad-crested and sharp-crested, are considered for validation purposes. The calculated overflow parameters such as pressure head distributions, velocity distributions, and water surface profiles are compared against experimental data as well as numerical results available in literature. A very good quantitative agreement has been obtained. The numerical model, thus, offers a good alternative to traditional experimental methods in the study of weir problems.

47. LV, X., ZOU, Q., REEVE, D.E. & ZHAO, Y.: "A preconditioned implicit free-surface capture scheme for large density ratio on tetrahedral grids", *Communications in Computational Physics*, *issue. 11*, pp. 215-248, DOI: 10.4208/cicp.170510.290311a, 2012
We present a three dimensional preconditioned implicit free-surface capture scheme on tetrahedral grids. The current scheme improves our recently reported method [10] in several aspects. Specifically, we modified the original eigensystem by applying a preconditioning matrix so that the new eigensystem is virtually independent of density ratio, which is typically large for practical two-phase problems. Further, we replaced the explicit multi-stage Runge-Kutta method by a fully implicit Euler integration scheme for the Navier-Stokes (NS) solver and the Volume of Fluids (VOF) equation is now solved with a second order Crank-Nicolson implicit scheme to reduce the numerical diffusion effect. The preconditioned restarted Generalized Minimal RESidual method (GMRES) is then employed to solve the resulting linear system. The validation studies show that with these modifications, the method has improved stability and accuracy when dealing with large density ratio two-phase problems.

48. MALKI, R., MASTERS, I., WILLIAMS, A.J. & CROFT, T.N.: “Planning Tidal Stream Turbine Array Layouts Using a Coupled Blade Element Momentum - Computational Fluid Dynamics Model” *Renewable Energy, vol. 63,* pp. 46-54, DOI: 10.1016/j.renene.2013.08.039., 2013
A coupled blade element momentum – computational fluid dynamics (BEM–CFD) model is used to conduct simulations of groups of tidal stream turbines. Simulations of single, double and triple turbine arrangements are conducted first to evaluate the effects of turbine spacing and arrangement on flow dynamics and rotor performance. Wake recovery to free-stream conditions was independent of flow velocity. Trends identified include significant improvement of performance for the downstream rotor where longitudinal spacing between a longitudinally aligned pair is maximised, whereas maintaining a lateral spacing between two devices of two diameters or greater increases the potential of benefitting from flow acceleration between them. This could significantly improve the performance of a downstream device, particularly where the longitudinal spacing between the two rows is two diameters or less. Due to the computational efficiency of this modelling approach, particularly when compared to transient computational fluid dynamics simulations of rotating blades, the BEM–CFD model can simulate larger numbers of devices. An example of how an understanding of the hydrodynamics around devices is affected by rotor spacing can be used to optimise the performance of a 14 turbine array is presented. Compared to a regular staggered configuration, the total power output of the array was increased by over 10%.

49. MALKI, R., MASTERS, I., WILLIAMS, A.J. & CROFT, T.N.: "The variation in wake structure of a tidal stream turbine with flow velocity", *International Conference on Computational Methods in Marine Engineering MARINE 2011, Lisbon, Portugal*, 2011
A combined Blade Element Momentum—Computational Fluid Dynamics (BEM-CFD) model is applied to a 10 m diameter tidal stream turbine blade and the supporting nacelle and tower structure in a 700 m long rectangular channel. The modelling approach is computationally efficient and is suitable for capturing the time-averaged influence of the turbine on the flow. A range of simulations are conducted for the purpose of undertaking a comparative study of the influence of the turbine on mean flow characteristics. Variations in flow structure around the turbine for different flow conditions were evaluated. Simulations are conducted for a range free-stream velocities typical of potential tidal stream deployment sites, typically up to 3.0 m/s. Velocity deficit profiles and wake dimensions are evaluated for each flow condition implemented. Downstream flow recovery is strongly linked to the flow velocity, and occurs over a longer distance with increasing velocity. For the range of velocities considered some properties, such as wake length and the maximum wake length location increase linearly, or nearly-linearly with velocity. Other properties, such as the maximum wake width, and the recovery distance downstream demonstrate a tendency to converge towards a constant value. The key findings of this study highlight the significance of the free-stream velocity as an influence on the flow structure around and downstream of a tidal stream turbine.

50. MALKI, R., MASTERS, I., WILLIAMS, A.J. & CROFT, T.N.: "The influence of tidal stream turbine spacing on performance", *EWTEC 2011, Southampton, UK*, Sep-11
Staggered three-turbine arrays are modelled using a Blade Element Momentum - Computational Fluid Dynamics model. The influence of the wakes behind two upstream turbines on the flow structure and the power output of a downstream turbine is evaluated. Longitudinal spacings between 1.0 and 10.0 diameters and lateral spacings between 1.5 and 5.0 diameters are considered. Significantly lower flow velocities were observed in turbine wakes compared to the free-stream. These were accompanied by higher velocities in the adjacent regions. Within the wake region, there was initially a region of significant negative acceleration due to the influence of the turbine. Laterally adjacent regions experience a counter-effect and hence, the flow accelerates. Downstream turbines in arrays with small longitudinal spacings (2.0 diameters or less) benefited from this feature. A steady recovery of the wake ensued. A complete recovery is almost achieved 40 diameters downstream. For very low lateral spacings within the upstream row of turbines (2.0 diameters or less), the downstream turbine was located within upstream wakes and its performance was severely compromised. However, for greater lateral spacing’s, the opposite effect was observed, and the downstream turbine benefited from flow acceleration between the two upstream turbines.

51. MALKI, R., TOGNERI, M., MASTERS, I., WILLIAMS, A.J. & CROFT, N.C.: "Computationally efficient approaches to the modelling of tidal stream turbines", *ENSUS 2011, Newcastle University, UK*, 2011
Tidal stream turbines (TSTs) extract energy from marine current flows; a satisfactory model of this system must address both the effects of the flow on the device and the device's impact on the marine environment. Marine flows are highly complex, and both turbulence and waves will significantly influence the conditions experienced by TSTs; thus we must find a way to model their effects. But a model capable of analysing only a single device is not satisfactory, as real TST installations are likely to consist of numerous devices arranged in layouts planned so as to maximise the power output of each turbine. This can be best achieved by striving to ensure that, as far as is possible, individual turbines are not deployed within the wake of upstream devices. However, depending on

dimensional constraints, which are likely to be determined by the boundaries and the bathymetry of a proposed deployment site, this may not be completely avoidable. Our task then becomes one of optimisation: how can we best balance these constraints? The need to take these practical considerations into account means that development of optimal devices for array deployment is a complex task. Computational fluid dynamics (CFD) can be used to assist the process, but traditional approaches that include discrete representation of the hydrofoils in the mesh can incur a prohibitive computational expense. Blade element momentum (BEM) theory is a very fast alternative approach that, when modified to account for a turbulent inflow, can be used to model lifetime effects such as fatigue on a turbine and its support structure. Combined BEM-CFD models attempt to employ the advantages of both formulations by using a standard CFD approach in the domain, but modelling the rotor behaviour with an embedded BEM description. This presentation will provide a description of the two approaches and make comparisons between the types of results that these computational models can provide. We discuss methods by which we incorporate the effects of marine turbulence into an existing BEM code, and present some results that show its influence on turbine power and loads. BEM-CFD simulations, although more computationally intensive, produce far more detail on the influence that tidal current turbines have on the fluid flow; we show how different operating conditions alter the wake behind a single turbine, and investigate the influence of wakes on other turbines in an array.

52. MCCALLUM, P., VENUGOPAL, V., FOREHAND, D. & SYKES, R.: "On the performance of an array of floating wave energy converters for different water depths", *33rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, California*, DOI: 10.1115/OMAE2014-24094, 8-13 June 2014
A frequency domain hydrodynamic assessment was carried out using WAMIT on buoy type wave energy converters (WECs), constrained to move in heave only. Control of the power take-off (PTO) system has been established through real control (damping resistance only) for an isolated WEC. This fixed value has then been applied to all WECs in an array of ten devices, set out in two rows. The array has been tested in six water depths, represented by the relative water depth d/ λ0, ranging from 0.25 to infinite depth, where λ0 is the resonant wavelength of an isolated WEC in infinitely deep water. Incremental reductions in water depth, result in an drop in peak q̄ -factor, which was also marked with a small shift in ka. It was deemed appropriate here to re-tune the PTO settings for the different water depths. The various interactions within the array were examined in more detail by considering the radiation forces between WECs. Results are presented, highlighting the most significant device interactions due to the variations in water depth. The growth and shift in ka of the peak forces are also evident in shallower water. Depth modified JONSWAP and Pierson-Moskowitz spectra have also been applied in order to calculate mean power production estimates for the various water depths. For the particular array and conditions considered, there was a clear downward trend in power captured when moving into progressively shallower water. This was in part due to the reduction in total energy available in the shallower spectra, but also because the frequency of peak performance of the array has shifted significantly.

53. MCNATT, J.C., VENUGOPAL, V., FOREHAND, D.I.M. & PAYNE, G.S.: "Experimental analysis of cylindrical wave fields", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
In a previous theoretical paper submitted to EWTEC, the authors showed that the wave energy converter (WEC) wave field can be accurately and analytically represented by cylindrical linear waves with the appropriate coefficients. In that paper, the coefficients were found computationally using the boundary-element method software, WAMIT. For the present paper, experiments were conducted in the newly refurbished University of Edinburgh Curved Wave Tank to determine the same cylindrical coefficients for progressive waves. The experiments employed two body geometries, an attenuator consisting of a horizontal pitching cylinder, and a terminator made up of a bottom-hinged flap. An array of 59 wave gauges was arranged in a circle-spoke pattern, where the circle of wave gauges was necessary for deriving the cylindrical coefficients, and the spokes, which extended radially further afield, were used for validation. Both the scattered and the radiated waves of the bodies were examined at three frequencies. High-order harmonics were present in a number of the wave fields, and tank reflections were problematic. Despite this, the linear analytical wave field, whose coefficients were found experimentally, agrees well with the experimentally measured linear wave field at points other than those used to derive the coefficients. The results serve to validate linear wave theory as it relates to the wave field and reinforce the concept that these waves can be used to compute WEC performance and wave farm interactions and impacts.

54. NAMBIAR, A.J., ET AL.: "State-of-the-art assessment and specification of data requirements for electrical system architectures", *Report to the European Commission*, 2014
This deliverable will consist of two major parts: A comprehensive review (Chapters 1-4) of all the electrical infrastructure technologies between the converter and the point of connection to the onshore electrical grid, including technologies currently used in offshore electrical networks, as well as those foreseen to be deployed in the near future. A set of operating regimes of the ocean energy conversion arrays in terms of their output power

(given as a statistical representation and as a set of representative time series), for the scenarios to be considered in the next tasks, as defined by WP1 and WP2 (Chapter 5).

55. NAMBIAR, A.J., COLLIN, A.J., KARATZOUNIS, S., KIPRAKIS, A.E., REA, J. & WHITBY, B.: "Optimising network design options for marine energy converter farms", *EWTEC conference, Nantes*, 7-10 Sep 2015
This paper introduces a techno-economic analysis framework to assess different transmission options for marine energy converter (MEC) farms. On the technical front, the feasibility of the transmission options considering supply quality constraints and the optimal sizing of reactive power compensation to allow maximum real power transfer capability in the subsea transmission cable have been considered. The economic viability of different transmission options are measured based on component costs and the costs associated with the transmission losses. A case study has been presented in the paper, which demonstrates the application of this techno-economic analysis framework on a range of MEC farm sizes and distances from the shore. The results characterise the performance of different transmission system options with respect to the three key design parameters, distance to shore, array power and transmission voltage, and provide guidance for system design.

56. NAMBIAR, A.J., ET AL.: "An offshore network layout and technology design tool", *Report to the European Commission*, 2014
This document presents the work done against Deliverable 3.2 'An offshore network layout and technology design tool'. The output of D3.2 is a host of integrated Python scripts which provide the necessary functionality for performing the technical assessment of array layouts. The purpose of this accompanying document is to provide information on the code development and structure. All codes are available on the DTOcean file server; details of these codes are included in the Appendices of this document. Two overlapping tasks are feeding into D3.2: Task 3.3 'Offshore electrical network layout modelling and design' and Task 3.4, 'Offshore electrical network components selection'. Task 3.3 can be considered the foundation of all subsequent work in WP3, as its key objective is to allow for the representation and analysis of electrical networks within the software environment. The main output of this task is the development of a power flow solver and its integration with spatial analysis and database software. Task 3.4 extends the functionality of the developed power flow routine to consider the electrical and mechanical aspects of the offshore electrical network components such as connector types (wet vs. dry), cable ratings and types (fixed/static vs. flexible/dynamic), umbilical etc., and combines them into a single cost function. At this stage of the project, the main output of this task is provision for the inclusion in the decision making (i.e. optimisation) process of the design tool of the electrical and mechanical aspects of the various offshore electrical network components. Task 3.4 is ongoing and scheduled for completion by Month 12. In accordance with project specifications, all aspects of the design tool are being developed in Python. The inputs (design scenarios), parameters (component specifications) and outputs (final network design specifications) are stored in a Structured Query Language (SQL) database. The Python code is integrated with an open source Geographical Information System (GIS) software, which also functions as the Graphical User Interface (GUI) for the design tool. The selected software is: Python v2.7.5, PostgreSQL v9.3 and Quantum GIS (QGIS) v2.2.0.

57. NAMBIAR, A.J., FOREHAND, D.I.M., KRAMER, M.M., HANSEN, R.H. & INGRAM, D.M.: "Effects of hydrodynamic interactions and control within a point absorber array on electrical output", *International Journal of Marine Energy*, *vol. 9*, pp. 20-40, DOI: 10.1016/j.ijome.2014.11.002, 2015
A significant role is envisaged for ocean wave energy to meet the different renewable energy targets set by various governments and world bodies. To make use of this potential, the industry will soon be moving from sea testing of individual wave energy converters (WECs) to the deployment of arrays and farms of WECs. The total power extracted by an array of WECs is influenced by the hydrodynamic interactions between them, especially when the WECs are spaced very closely. By control of the power take-off (PTO) forces and moments acting on the WECs within the array, the hydrodynamic interactions between the WECs and the total power extracted by the array can be modified. In this paper, different resistive and reactive PTO control strategies, applied to a time-domain wave-to-wire model of a three-float Danish Wavestar device, are compared. The time-domain modelling approach, as opposed to the frequency-domain, allows the use of constraints on the maximum PTO moment to be applied in order to make the study realistic. In this paper, the effects that PTO control has on the hydrodynamic interactions between the floats and on the total power generated by the device, when placed in a range of irregular sea states, are studied. It was found that the performance of the three-float device improved as the sophistication of the PTO control strategy and the level of hydrodynamic interactions taken into account in the control problem increased. From among the different control strategies tested in this work, fully-coordinated global array control (matrix control) was found to maximise the time-averaged power generated by the array. Fully-coordinated control potentially enables wave farm developers and device designers to explore the opportunities of connecting and maximising energy yields from installations that will be necessary to contribute to meeting the 2020 and 2050 targets for offshore renewable energy.

58. NEILL, S.P.: "Impact of tidal energy arrays located in regions of tidal asymmetry", *2nd Oxford Tidal Energy Workshop (OTE 2013), Department of Engineering Science, Oxford University*, 18-19 March 2013
Tidal stream turbines are exploited in regions of high tidal currents. Such energy extraction will alter the regional hydrodynamics, 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. 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.

59. NEILL, S.P., HASHEMI, M.R. & LEWIS, M.J.: "Optimal phasing of the European tidal stream resource using the greedy algorithm with penalty function", *Energy*, *vol. 73*, pp. 997-1006, DOI: 10.1016/j.energy.2014.07.002, Aug-14
The regular periodicity of astronomical tides allows their accurate prediction, and so it should be possible to determine how best to optimise the future distribution of arrays of tidal energy devices for any shelf sea region. By considering together the magnitude and phase of tidal currents over a shelf sea region, maximum aggregated power generation, with minimal periods of low generation, can be deduced. Here, we make use of the greedy algorithm to optimise future exploitation of the tidal stream resource over the northwest European shelf seas, a region which contains a world-leading tidal energy resource. We also apply a penalty function to the greedy algorithm, favouring the selection of future hypothetical sites where power generation would be out-of-phase with previously developed sites. Our results demonstrate that the Pentland Firth and Channel Islands would be optimal sites for parallel development for relatively low numbers of arrays, with important contributions from the Irish Sea for larger scale exploitation. Although there is minimal phase diversity between European tidal stream sites to deliver firm power generation, it is possible that the vertical tide could contribute to such baseload through the parallel development of lagoons or impoundments.

60. NEILL, S.P., HASHEMI, M.R. & LEWIS, M.J.: "The role of tidal asymmetry in characterizing the tidal energy resource of Orkney", *Renewable Energy*, *vol. 68*, pp. 337-350, DOI: 10.1016/j.renene.2014.01.052, Aug-14
When selecting sites for marine renewable energy projects, there are a wide range of economical and practical constraints to be considered, from the magnitude of the resource through to proximity of grid connections. One factor that is not routinely considered in tidal energy site selection, yet which has an important role in quantifying the resource, is tidal asymmetry, i.e. variations between the flood and ebb phases of the tidal cycle. Here, we present theory and develop a high-resolution three-dimensional ROMS tidal model of Orkney to examine net power output for a range of sites along an energetic channel with varying degrees of tidal asymmetry. Since power output is related to velocity cubed, even small asymmetries in velocity lead to substantial asymmetries in power output. We also use the 3D model to assess how tidal asymmetry changes with height above the bed, i.e. representing different device hub heights, how asymmetry affects turbulence properties, and how asymmetry is influenced by wind-driven currents. Finally, although there is minimal potential for tidal phasing over our study site, we demonstrate that regions of opposing flood- versus ebb-dominant asymmetry occurring over short spatial scales can be aggregated to provide balanced power generation over the tidal cycle.

61. NEILL, S.P., LEWIS, M.J., HASHEMI, N.J., SLATER, E., LAWRENCE, J. & SPALL, S.A.: "Inter-annual and inter-seasonal variability of the Orkney wave power resource", *Applied Energy*, *vol. 132*, pp. 339-348, DOI: 10.1016/j.apenergy.2014.07.023, Nov-14
The waters surrounding the Orkney archipelago in the north of Scotland are one of the key regions in the world suitable for exploitation of both wave and tidal energy resources. Accordingly, Orkney waters are currently host to 1.08 GW of UK Crown Estate leased wave and tidal energy projects, with a further 0.5 GW leased in the southern part of the adjacent Pentland Firth. Although several wave resource models exist of the region, most of these models are commercial, and hence the results not publicly available, or have insufficient spatial/temporal resolution to accurately quantify the wave power resource of the region. In particular, no study has satisfactorily resolved the inter-annual and inter-seasonal variability of the wave resource around Orkney. Here, the SWAN wave model was run at high resolution on a high performance computing system, quantifying the Orkney wave power resource over a ten year period (2003–2012), a decade which witnessed considerable inter-annual variability in the wave climate. The results of the validated wave model demonstrate that there is considerable variability of the wave resource surrounding Orkney, with an extended winter (December–January–February–March, DJFM) mean wave power ranging from 10 to 25 kW/m over the decade of our study. Further, the results demonstrate that there is considerably less uncertainty (30%) in the high energy region to the west of Orkney during winter months, in contrast to much greater uncertainty (60%) in the lower energy region to the east of Orkney. The DJFM wave resource to the west of Orkney correlated well with the DJFM North Atlantic Oscillation

(NAO). Although a longer simulated time period would be required to fully resolve inter-decadal variability, these preliminary results demonstrate that due to considerable inter-annual variability in the NAO, it is important to carefully consider the time period used to quantify the wave power resource of Orkney, or regions with similar exposure to the North Atlantic. Finally, our study reveals that there is significantly less variability in the practical wave power resource, since much of the variability in the theoretical resource is contained within relatively few extreme events, when a wave device enters survival mode.

62. OIKONOMOU, C. & AGGIDIS, G.A.: "Wave energy resource assessment in the seas around Greece: Estimation and prospects", *International Conference on Applied Coastal Research, Florence, Italy*, 28 Sep - 1 Oct 2015
This paper reviews the progress made in assessing the wave energy resource in the Aegean and Ionian Sea. The area of interest is characterized by complex topography, and strong winds. Although the overall wave energy potential is not as high as it is in other Mediterranean countries, locations offshore the Greek pelago could still act as a wave energy operating sites, contributing in the development of sustainable engineering and the reduction of carbon emissions. Various studies in the past established wave forecasting models and coupled wind-wave models to assess the basic wave characteristics (i.e. significant wave height and period) in the Aegean and Ionian Sea. Afterwards, further research based on such models and measurements, presented promising areas where Wave energy converters could be deployed. The topographic complexity and the distribution of islands, mainly in the Aegean Sea, form channelling effects favouring the wave energy potential. The mean exploitable wave energy for the country based on assessment studies was estimated to be 4-11 kW/m, which could be satisfactory, along with the suitable technology utilizations. Areas that are considered to be favourable wave energy sites, are the region south of the island of Crete and the Southwest region of Ionian Sea. The current study summarizes past projects in the numerical modelling, measurements and forecasting of wave characteristics and the progress made on wave energy appraisal, along with suggestions for future improvements.

63. OIKONOMOU, C., JAMOMOH, A.J. & AGGIDIS, G.A.: "Processes leading to the formation of Hybrid event beds: a field study", *Panhellenic Symposium on Oceanography and Fisheries, Mytilene, Greece*, 14-17 May 2015
Knowledge on the formation and frequency of Hybrid event beds in distal basin locations is limited. This paper attempts to interpret types of sand-beds encasing a mud-rich interval, making use of existing alternative facies models and scenarios. The study area is well-known for the existence of such exposed sequences, formed during the Silurian era (400-500 million years ago). It is more likely that the majority of Hybrid event beds in the area of interest are the result of a combination of vertical and lateral flow properties segregation.

64. OLCZAK, A., STALLARD, T., FENG, T. & STANSBY, P.K: "Comparison of a RANS blade element model for tidal turbine arrays with laboratory scale measurements of wake velocity and rotor thrust", *Journal of Fluids and Structures*, *vol. 64*, pp. 87–106, DOI: 10.1016/j.jfluidstructs.2016.04.001, Jul-16
A Reynolds averaged Navier Stokes (RANS) model has been compared with laboratory scale measurements of the loading and wake of arrays of horizontal axis three-bladed rotors. The diameter D of each rotor was 0.27 m and axis was at mid depth in a channel of depth 1.67D and width 11.5D. Mean flow speed was 0.46 m/s, giving a Reynolds number of 2×105, with turbulence intensity of 12%. The commercial software StarCCM+ is employed. Steady flow is modelled and each rotor represented by imposing radial variation of streamwise force on the rotor defined by a blade element method. When experimental values of turbulent kinetic energy and dissipation rate are defined at the model inflow, the transverse profile of depth-averaged velocity of a single rotor wake is predicted reasonably for downstream distances greater than 4D. Within 0.5D to 2Ddownstream of the rotor plane the wake is approximately axisymmetric and both streamwise velocity and wake rotation are reasonably well predicted for radii greater than half the rotor radius. Inclusion of tip generated turbulent kinetic energy as predicted by blade resolved RANS CFD improves predictions of streamwise velocity and wake rotation within 4D downstream. For a single row of rotors partially spanning the channel the increase of thrust coefficient relative to an isolated rotor due to global and local blockage is predicted, but the overall magnitude of thrust is overpredicted. Downstream of a single row the velocity deficit along the axis of each rotor is closely predicted while the deficit between adjacent wakes is underpredicted until approximately 8Ddownstream. For a second row of rotors located at 8D downstream the square of the rotor averaged velocity, indicative of thrust, is predicted to within 3% and 12% respectively for rotor axes aligned and staggered relative to those on the front row. For these downstream rotor positions similar accuracy may be obtained by superposition of the self-similar velocity deficit profile of isolated rotor wakes only. For multiple rows, thrust on the front row of rotors is increased relative to the same row in isolation. Rotors on downstream rows partly exposed to the higher velocity flow bypassing the array also experience high values of thrust. For arrays of up to twelve rotors the average thrust of an individual turbine in a row is typically predicted to within 10% for the first row and 20% for the second row and within 38% for the inner rotors of the third row. The accuracy of a RANS blade element method using commercially available software has

thus been assessed for the complex wake flows of arrays of up to twelve three-bladed rotors in a shallow turbulent flow.

65. OLCZAK, A., SUDALL, D., STALLARD, T. & STANSBY, P.K.: "Evaluation of RANS BEM and self-similar wake superposition for tidal stream turbine arrays", *Proc. 11th EWTEC*, 7-10 Sep 2015
Prediction of the loading and energy yield of a turbine within an array requires knowledge of the onset flow profile due to the wakes of turbines located upstream. This depends on many factors and processes including the geometry of the turbine and supporting structure, turbine operating point, array layout and the profiles of velocity and turbulence of the ambient flow. Various studies have employed CFD to simulate the flow-field downstream of single and multiple turbines using actuator disk and RANS-BEM methods. However limited evaluation has been presented for wake interaction. In this study two numerical approaches for modelling the wakes of arrays of turbines are evaluated by comparison to experimental data from a study of a single wake and the merging wakes of a single row of five turbines. With RANS-BEM the transverse profile of velocity is simulated to reasonable accuracy over the far-wake region provided that the ambient flow turbulent kinetic energy and dissipation rate are representative. Improved agreement of the velocity-profile over the near-wake region is obtained by representing the elevated turbulent kinetic energy over the tip vortex region. The magnitude of TKE in this region is based on prior blade modelled simulations and experiments. The second approach assumes that the self similar far wake profile of a single turbine may be superimposed for multiple turbines based on local velocity conditions. This is highly efficient but does not account for the device-scale bypass flow. Mean loading of a rotor is a function of the mean of velocity squared integrated over the rotor plane. For downstream rows located at 8D downstream this is predicted by both methods to within 4% and 12% for aligned and staggered turbines respectively.

66. PASCAL, R. & BRYDEN, I.: "Directional spectrum methods for deterministic waves", *Ocean Engineering*, *vol. 38*, *issue. 13*, pp. 1382-1396, Sep-11
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 byJefferys (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.

67. PENG, Z., GENG, Z., NICHOLAS, M., LARAMEEE, R.S., CROFT, N., MALKI, R., MASTERS, I. & HANSEN, C.: “Visualization of Flow Past a Marine Turbine: The Information-Assisted Search for Sustainable Energy” *Computing and Visualization in Science, vol. 16,* issue*. 3*, pp 89-103, http://dx.doi.org/10.1007/s00791-014-0229-4, Jun 2013
Interest in renewable, green, and sustainable energy has risen sharply in recent years. The use of marine turbines to extract kinetic energy from the tidal current is gaining popularity. CFD modeling is carried out to investigate the surrounding flow behavior and thus develop effective marine turbine systems. However, visualizing the simulation results remains a challenging task for engineers. In this paper, we develop, explore and present customized visualization techniques in order to help engineers gain a fast overview and intuitive insight into the flow past the marine turbine. The system exploits multiple-coordinated information-assisted views of the CFD simulation data. Our application consists of a tabular histogram, velocity histogram, parallel coordinate plot, streamline plot and spatial views. Information-based streamline seeding is used to investigate the behavior of the flow deemed interesting to the engineer. Specialized, application-specific information based on swirling flow is derived and visualized in order to evaluate turbine blade design. To demonstrate the usage of our system, a selection of specialized case scenarios designed to answer the core questions brought out by engineers is described. We also report feedback on our system from CFD experts researching marine turbine simulations.

68. PETLEY, S. & AGGIDIS, G.: "Swansea Bay tidal lagoon annual energy estimation", *Ocean Engineering*, *vol. 111*, pp. 348–357, DOI: 10.1016/j.oceaneng.2015.11.022, 01-Jan-16
UK Energy policy is focused on the challenges posed by energy security and climate change, however, efforts to develop a low-carbon economy have overlooked tidal energy a vast and unexploited worldwide resource. Since 1981, UK tidal lagoon schemes have been recommended as an economically and environmentally attractive alternative to tidal barrages. More recently, two proposals for tidal lagoons in Swansea Bay have emerged and there have been several reports documenting the potential to harness significant tidal energy from Swansea Bay using a tidal lagoon. This paper assists in determining a realistic approximation of the energy generation potential in Swansea Bay, a numerical estimation is obtained from a zero dimension, 0D, ‘backwards difference’ computational model, utilising the latest turbine data available and high-resolution bathymetric data. This paper

models the behaviour of the tidal lagoon in dual mode generation, in line with the above proposals. The results of model testing using a variety of fixed and variable parameters are displayed. The ebb mode model with provision for pumping at high tide is then explored further by carrying out optimisations of the starting head, number of turbines and turbine diameter in order to determine the maximum annual energy output from the tidal lagoon.

69. PÉREZ-ORTIZ, A., PESCATORE, J. & BRYDEN, I.: "A Systematic Approach to Undertake Tidal Energy Resource Assessment with Telemac-2D", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
This paper presents a systematic approach to tidal channel simulation using a finite element model which solves depth-averaged free surface flow equations. A formal resource assessment methodology for tidal energy development in known tidal regimes may be established by following procedures outlined herein. Channel geometry, boundary specifications, planform features and momentum sinks from tidal turbines are considered in assessing the physical potential of energy extraction at a site. The methodology is subsequently applied to an actual case study, the Pentland Firth.

70. POTTER, G., TUNSTALL, T., MASTERS, I. & CHAPMAN, J.: "Growing The Marine Energy Supply Chain In Wales" *Educational Alternatives, vol. 12,* ISSN 1313-2571, 2014
To mitigate Climate Change and reduce greenhouse gas emissions, Europe is currently the World leader for exploiting one of the most significant sources of global untapped renewable energy; energy from our oceans. Within Europe, the UK is foremost to establish a sustainable marine energy industry, through research, development and supply chain growth. This article will examine the Skills and Training Needs Analysis work undertaken by Swansea University, to provide training courses designed to grow the marine energy supply chain within Wales and thus support and sustain Europe's leading status.

71. RANSLEY, E. & GREAVES, D.: "Investigating interaction effects in an array of multi-mode wave energy converters,", *International Workshop on Water Waves and Floating Bodies, Copenhagen, Denmark*, 2012
A number of wave energy device developers have now successfully tank-tested scale-model prototypes and several are attempting full-scale deployment at sea. Many believe the superior survivability of simple, buoy-like designs make them the most economically viable solutions. Developers of so called 'point-absorbers' hope to install multiple devices in arrays, offering considerable savings in terms of moorings, grid connections and maintenance. It is recognised that the additional hydrodynamic interactions between devices, from scattered and radiated waves within the array, can significantly alter the surface elevation and enhance the interaction factor, q, defined as the ratio of power from the array to that from the same number of isolated devices. In contrast to traditional offshore structures, like floating platforms, enhancements due to these interactions could have practical benefit in the effective design of wave energy converter (WEC) arrays. However, these interactions depend on numerous system variables leading to a complex array transfer function, referred to here as the Configuration Response Amplitude Operator (CRAO). There exists a CRAO specific to each possible configuration, consisting of a set of q-factors which describe the output of the array, compared to isolated devices, as a function of incident wave frequency and direction. Research directly concerning WEC arrays has focussed primarily on optimal response; however, there has been limited success in designing optimal array configurations over a range of incident wave conditions. Some novel control methods have been suggested and this work considers combining multiple oscillatory modes as one possible method, differing from the majority of the literature which considers single mode oscillation only (usually heave).

72. ROSE, S., ORDONEZ-SANCHEZ, S., LEE, K.H, JOHNSTONE, C., JO, C.H., MCCOMBES, T. & GRANT, A.: "Tidal turbine wakes: small scale experimental and initial computational modelling", *EWTEC 2011, Southampton, UK*, Sep-11
The study of wake propagation is essential to understand the evolution of the wake behind a tidal device, which will differ enormously in comparison with similar technologies (i,e wind turbines) due to the boundary conditions. Other environmental effects such as sediment transport, salinity, turbidity of the water can also be quantified through a wake characterisation analysis. Therefore, the wake pattern will dictate how turbines will be placed on site in order to avoid a decrease in power output when the devices are installed in arrays. In recent times a considerable effort has gone into modelling wakes, both through physical testing and computational simulation, however, a discrepancy between the two approaches is often apparent. This paper seeks to present experimental work 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.

73. SANKARAN IYER, A., COUCH, S.J, HARRISON, G.P. & WALLACE, A.R.: "Variability and phasing of tidal current energy around the United Kingdom", *Renewable Energy*, *vol. 51*, pp. 343-357, DOI: 10.1016/j.renene.2012.09.017, 2012
Tidal energy has the potential to play a key role in meeting renewable energy targets set out by the United Kingdom (UK) government and devolved administrations. Attention has been drawn to this resource as a number of locations with high tidal current velocity have recently been leased by the Crown Estate for commercial development. Although tides are periodic and predictable, there are times when the current velocity is too low for any power generation. However, it has been proposed that a portfolio of diverse sites located around the UK will deliver a 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 of tidal current energy industry development. These scenarios incorporate constraints relating to assessment of the economically harvestable resource, tidal technology potential and the practical limits to energy extraction dictated by environmental response and spatial availability of resource. The final scenario is capable of generating 17 TWh/year with an effective installed capacity of 7.8 GW, at an average capacity factor of 29.9% from 7 major locations. However, it is concluded that there is insufficient diversity between sites suitable for first generation tidal current energy schemes for a portfolio approach to deliver firm power generation.

74. SANKARAN IYER, A., MACGILLVRAY, A., COUCH, S., WINSKEL, M., JEFFREY, H., WALLACE, A.R. & BRYDEN, I.: "Analysis of tidal Current Energy scenarios in UK and Levelised Cost of Energy", , *1st Asian Wave and Tidal Energy Conference Series, Jeju Island, Korea*, 27-30 Nov 2012
Technology for harvesting energy from tidal current movement has reached a development phase. Numerous devices are being tested in full scale for efficient operations and survivability. But in order to fully reach commercialization, it is necessary to complete detailed analysis to assess the potential resource, energy generation capabilities and assess the cost of energy from tides. The analysis presented in this paper aims to identify the key parameters in terms of investment costs that are needed to progress the marine sector (with particular emphasis on tidal). Taking a simple single factor learning rate model, the analysis also highlights the sensitivity of the overall cost of commercializing marine energy to key input parameters. The paper also considers the implications of the aggregated analysis of costs and cost uncertainties for the management of marine innovation, in terms of the relative contributions of different learning effects (learning by doing, learning by research, technology transfer and spill-over). This exercise will highlight how cost competitive first generation tidal current energy is and which parameters it is most sensitive to.

75. SAULNIER, J-B., MAISONDIEU, C., ASHTON, I. & SMITH, G.H.: "Sea state directional analysis near the Wave Hub test facility", *Journal of Applied Ocean Research*, *vol. 37*, pp. 1-21, 2012
This paper presents an analysis of sea states carried out from extended wave measurements realized near the Wave Hub wave energy test facility in Cornwall (UK). The space directional information is derived from the spectro-directional processing of time-domain data provided by an array of four independent SEAWATCH Mini II displacement buoys separated by an approximate average distance of 500 m. It is observed that, even though the size of the array is small compared to the local wave trains' length, the estimation of the directional spectra – using maximum entropy and likelihood methods – may sometimes exhibit certain space variability over the array. It was also observed that the tidal currents variations produced a significant influence upon the wave directional estimation and wave spectral parameters. Spectro-directional partitioning and wave system tracking were subsequently applied and this emphasized the influence of tide variations upon the individual swells and wind-seas as measured by the buoys. This paper, therefore, also illustrates the relevance of applying partitioning and tracking procedures for the identification of wave systems in oceanographic and wave energy studies.

76. SHAH, K., MYERS, L.E. & BAHAJ, A.S.: "Scale experimental modelling of a multiple row tidal array", *2nd Asian Wave and Tidal Energy Conference, Japan*, 28 July - 1 Aug 2014
This paper describes the experimental modelling of a tidal turbine array composed of 10 small-scale static actuator devices and how the results relate to a full scale tidal turbine array. The array employed an offset-row structure. Several hundred discrete measurements were acquired at the array vertical centre plane across the flume and far downstream of each device using a set of four Acoustic Doppler Velocimeters mounted on an automated positioning carriage. The resulting flow field shows devices in rows further downstream see a more turbulent flow field and experience a drop in possible energy extraction as measured by the thrust force experienced on the actuator disks. As the array grows in size, the turbulence intensity is shown to increase and ambient flow structures are unable to penetrate into the array.

77. STALLARD, T., COLLINGS, R., FENG, T. & WHELAN, J.I.: "Interactions Between Tidal Turbine Wakes: Experimental Study of a Group of 3-Bladed Rotors", *Phil Trans R Soc Part A*, *vol. 371*, DOI: 10.1098/rsta.2012.0159, 2013

It is well known that a wake will develop downstream of a tidal stream turbine due to extraction of axial momentum across the rotor plane. To select a suitable layout for an array of horizontal axis tidal stream turbines it is important to understand the extent and structure of the wakes of each turbine. Studies of wind turbines and isolated tidal stream turbines have shown that the velocity reduction in the wake of a single device is a function of the rotor operating state (specifically thrust) and that the rate of recovery of wake velocity is dependent on mixing between the wake and the surrounding flow. For an unbounded flow the velocity of the surrounding flow is similar to that of the incident flow. However, the velocity of the surrounding flow will be increased by the presence of bounding surfaces formed by the bed and the free surface and by adjacent devices. This paper presents the results of a study investigating the influence of such bounding surfaces on the structure of the wake of tidal stream turbines.

78. STANSBY, P.K. & STALLARD, T: "Fast optimisation of tidal stream turbine positions for power generation in small arrays with low blockage based on superposition of self-similar far-wake velocity deficit profiles", *Renewable Energy*, *vol. 92*, pp. 366–375, DOI: 10.1016/j.renene.2016.02.19, Jul-16
Far wake velocities of a single horizontal axis three-bladed turbine in shallow flow have been measured previously in the laboratory and shown to have self-similar velocity deficit profiles. Wake velocities of arrays of turbines with one, two and three transverse rows have also been measured and simply superimposing the velocity deficits for a single turbine is shown to give accurate prediction of combined wake width and velocity deficit, accounting for variable downstream blockage through volume flux conservation. Array efficiency is defined as the ratio of total power generated to what would be generated by the same turbines in isolation. From prescribed initial turbine positions, generally determined intuitively or by practical considerations, adjusting the turbine positions to increase the power from each turbine, using the chain rule, shows that relatively small movements of 3–4 rotor diameters may increase array efficiency to over 90%.

79. STRATIGAKI, V., TROCH, P., STALLARD, T., FOREHAND, D., FOLLEY, M., KOFOED, J-P., BENOIT, M., BABARIT, A., VANTORRE, M., & KIRKEGAARD, J.: "Sea-state modification and heaving float interaction factors from physical modelling of arrays of wave energy converters", *Journal of Renewable and Sustainable Energy*, *vol. 7*, *issue. 6*, DOI: 10.1063/1.4938030, *ISSN: 1941-7012*, Nov-15
Wave energy converters (WECs) extract energy from ocean waves and have the potential to produce a significant amount of electricity from a renewable resource. However, large “WEC farms” or “WEC arrays” (composed of a large number of individual WECs) are expected to exhibit “WEC array effects”. These effects represent the impact of the WECs on the wave climate at an installation site, as well as on the overall power absorption of the WEC array. Tests have been performed in the Shallow Water Wave Basin of DHI (Denmark) to study such “WEC array effects”. Large arrays of up to 25 heaving point absorber type WECs have been tested for a range of geometric layout configurations and wave conditions. Each WEC consists of a buoy with a diameter of 0.315m. Power take-off was modeled by realizing friction basedenergy dissipation through damping of the WECs' motion. The produced database is presented: WEC response, wave induced forces on the WECs, and wave field modifications have been measured. A first understanding of WEC array effects is obtained. This unique experimental set-up of up to 25 individual WEC units in an array layout, placed in a large wave tank, is at present the largest set-up of its kind studying the important WEC array effects. The data obtained from these experimental tests will be very useful for validation and extension of numerical models. This model validation will enable optimization of the geometrical layout of WEC arrays for realistic wave farm applications and reduction of the cost ofenergy from wave energy systems.

80. STRATIGAKI, V., TROCH, P., STALLARD, T., FOREHAND, D., KOFOED, J.P., FOLLEY, M., BENOIT, M., BABARIT, A., & KIRKEGAARD, J.: "Wave basin experiments with large wave energy converter arrays to study interactions between the converters and effects on other users in the sea and the coastal area.", *Energies*, pp. 701-734, 7
Experiments have been performed in the Shallow Water Wave Basin of DHI (Hørsholm, Denmark), on large arrays of up to 25 heaving point absorber type Wave Energy Converters (WECs), for a range of geometric layout configurations and wave conditions. WEC response and modifications of the wave field are measured to provide data for understanding WEC array interactions and to evaluate array interaction numerical models. Each WEC consists of a buoy with a diameter of 0.315 m and power take-off (PTO) is modeled by realizing friction based energy dissipation through damping of the WEC's motion. Wave gauges are located within and around the WEC array. Wave conditions studied include regular, polychromatic, long- and short-crested irregular waves. A rectilinear arrangement of WEC support structures is employed such that several array configurations can be studied. In this paper, the experimental arrangement and the obtained database are presented. Also, results for wave height attenuation downwave a rectilinear array of 25 heaving WECs are presented, for the case of irregular waves. Up to 16.3% and 18.1% (long-crested) and 11.2% and 18.1% (short-crested waves) reduction in significant wave height is observed downwave the WEC array, for the radiated wave field only and for the combination of

incident-diffracted-radiated (perturbed) wave field, respectively. Using spectra at different locations within and around the array, the wave field modifications are presented and discussed.

81. STRATIGAKI, V., TROCH, P., STALLARD, T., FOREHAND, D., KOFOED, J.P., FOLLEY, M., BENOIT, M., BABARIT, A., VANTORRE, M. & KIRKEGAARD, J.: "Large scale experiments with point absorber type wave energy converters: the WECwakes database.", *In the Proceedings of the 5th International Conference on the Application of Physical Modelling to Port and Coastal Protection - Coastlab14; Varna, Bulgaria*, 29 Sep - 2 Oct 2014
The shrinking reserves of fossil fuels in combination with the increasing energy demand have enhanced the interest in renewable energy sources, including wave energy. In order to extract a considerable amount of wave power, large numbers of Wave Energy Converters will have to be arranged in arrays or farms using a particular geometrical layout. The operational behaviour of a single device may have a positive or negative effect on the power absorption of the neighbouring WECs in the farm (near-field effects). Moreover, as a result of the interaction between the WECs within a farm, the overall power absorption and the wave climate in the lee of the WECs is modified, which may influence neighbouring farms, other users in the sea or even the coastline (far-field effects). Several numerical studies on large WEC arrays have already been performed, but large scale experimental studies on near-field and far-field wake effects of large WEC arrays are not available in literature. Within the HYDRALAB IV European programme, the research project WECwakes has been introduced to perform large scale experiments in the Shallow Water Wave Basin of DHI, in Denmark, on large arrays of point absorbers for different layout configurations and inter-WEC spacings. The aim is to validate and further develop the applied numerical methods, as well as to optimize the geometrical layout of WEC arrays for real applications.

82. SUDALL, D., OLCZAK, A., STALLARD, T. & STANSBY, P.K.: "Simplified Wake Models for Small Tidal Farms: Reduced Scale Evaluation and Array Loading Study", *Oxford Tidal Energy Workshop, Oxford, United Kingdom*, 23-24 March 2015
Various models have been employed to estimate velocity deficit downstream of horizontal axis tidal turbines. In this study, prediction of loads on downstream turbines using self-similar superposition, developed in [1], is compared to experiments and RANS-BEM models for multiple rows of scaled rotors. It is found to compare well for centre array turbines but less so on outer array edge turbines. The superposition model is employed to evaluate the impact of yaw strategy on energy yield and load variation from a small tidal farm at the MeyGen site. Continuous yaw offers 24% greater energy yield over a fixed system. Peak mean loads on the most heavily loaded turbine in the array are 17% greater than the least loaded turbine.

83. TABOR, G.R., GEBRESLASSIE, M.G. & BELMONT, M.R.: "Investigation of the influence of turbine to turbine interaction on their performance using OpenFOAM", *Oxford Tidal Energy Workshop, Oxford, United Kingdom*, pp. 11-12, 29-30 March 2012
This paper presented the influence of turbine to turbine interaction on the performance of individual turbines using a new CFD based model, immersed body force (IBF). The results showed that a lateral proximity of turbines can improve the performance of individual turbines in a farm compared to isolated devices due to a blockage effect. However, this might have a negative effect on downstream turbines that can affect the overall power output of the farm, which opens the way for further investigation using upstream and downstream turbines to obtain an optimized location of the devices.

84. THOMAS, A., MASON-JONES, R., TURNER, D., O'DOHERTY, T., O'DOHERTY, D.M & MASON-JONES, A.: "Tidal and marine energy in the UK – identifying the future challenges for supply chain development", *11th International Conference on Manufacturing Research, Cranfield, United Kingdom*, 2013
The purpose of this paper is to investigate the current technical and operational supply chain issues surrounding the development of tidal and marine energy production in the UK. The paper outlines the market and growth potential of tidal energy production in the UK before identifying the key supply chain themes surrounding tidal energy production including an analysis of the portability and transferability of current supply chain thinking and development from other renewable energy systems such as wind turbine technology towards the development of tidal energy supply chain systems. The paper closes by identifying the major challenges that the UK supply chain must overcome in order to develop a comprehensive and robust supply chain system.

85. TOGNERI, M., & MASTERS, I.: "Micrositing variability and mean flow scaling for marine turbulence in Ramsey Sound", *Journal of Ocean Engineering and Marine Energy*, DOI: 10.1007/s40722-015-0036-0, 2015
We present turbulence results from two acoustic Doppler current profiler measurement campaigns carried out in Ramsey Sound at two locations within 50 m of one another. The first measurements were taken in 2009 and the second in 2011; both include a complete spring–neap cycle. In this paper we characterise turbulence through turbulent kinetic energy (TKE) density and integral lengthscales and their relationships with one another and with mean flow parameters. We briefly describe the methods used to calculate these parameters. We find that a flood–ebb asymmetry is present in the data from both measurement campaigns, but although the flood tides are similar

at both locations, the ebb tides are much more energetic in the 2011 data than the 2009 data. We suggest that this may be due to differences in seabed features between the two measurement locations. Dimensional analysis is employed to investigate how TKE scales with mean flow velocity; we find that the expected quadratic scaling is not well supported by the data at either measurement location. As a consequence, flows that have more energetic turbulence may instead appear to be less turbulent if judged by turbulence intensity. We investigate the correlation between lengthscales and TKE density and find that it is highly site-specific: it should not be assumed that for a given measurement location highly energetic turbulence is associated with larger flow structures or vice versa.

86. TROCH, P., STRATIGAKI, V., STALLARD, T., FOREHAND, D., FOLLEY, M., KOFOED, J.P., BENOIT, M., BABARIT, A., GALLACH SÁNCHEZ. D., DE BOSSCHER, L., RAUWOENS, P., ELSÄSSER, B., LAMONT-KANE, P., MCCALLUM, P., MCNATT, C., ANGELELLI, E., PERCHER, A., CARPENTERO MORENO, E., BELLEW, S., DOMBRE, E., CHARRAYRE, F., VANTORRE, M., KIRKEGAARD, J., & CARSTENSEN, S.: "Physical Modelling of an Array of 25 Heaving Wave Energy Converters to Quantify Variation of Response and Wave Conditions", *10th EWTEC Conference, Aalborg, Denmark*, 2013
Experiments have been performed in the Shallow Water Wave Basin of DHI, in Denmark, on large arrays of up to 25 heaving point absorbers for a range of layout configurations and wave conditions. Float response and modification of the wave field are measured to provide data suitable for the evaluation of array interaction models and environmental scale models. Each wave energy converter unit has a diameter of 0.315 m and power absorption is due to friction of both a power take off system and bearings. Response is measured on all floats and surge force on five floats. Wave gauges are located within and around the array. Wave conditions studied include regular waves and both long- and short-crested irregular waves. A rectilinear arrangement of support structures is employed such that several float configurations can be studied. A summary is presented of the experimental arrangement with particular emphasis on the individual wave energy converters and wave conditions employed. Reasonable agreement is observed between measured response for single floats and power output and float response predicted using a linear time domain model. For an array of 25 floats, up to 16.3% reduction of significant wave height is observed down-wave and 10.8% increase observed upwave for unidirectional irregular waves due to wave radiation by the heaving WECs. Spectra at different locations within and around the array show the wave field modifications.

87. TROCH, P., STRATIGAKI, V., STALLARD, T., FOREHAND, D., FOLLEY, M., KOFOED, J.P., BENOIT, M., BABARIT, A., VANTORRE, M. & KIRKEGAARD, J.: "An overview of the WECwakes project: physical modeling of an array of 25 wave energy converters.", *In the Proceedings of the 3rd IAHR Europe Congress, Porto, Portugal*, 14-16 April 2014
Experiments have been performed in the DHI Shallow Water Wave Basin (Denmark), on large arrays of up to 25 heaving point absorber Wave Energy Converters (WECs), for a range of geometric layout configurations and wave conditions. WEC response, surge forces on the WECs and modification of the wave field are measured to provide data for the understanding of WEC array interactions/effects. Wave conditions studied, include regular, polychromatic, long- and short-crested irregular waves. The experimental arrangement and the obtained database are presented. For irregular long-crested waves, up to 18.1% attenuation of significant wave height is observed downwave a rectilinear array of 25 heaving WECs.

88. ZANGIABADI, E., EDMUNDS, M., FAIRLEY, I.A., TOGNERI, M., WILLIAMS, A.J., MASTERS, I. & CROFT, N.S, I. & KARUNARATHNA, H.: “Computational Fluid Dynamics and Visualisation of Coastal Flows in Tidal Channels Supporting Ocean Energy Development” *Energies, vol. 8*, pp. 5997-6012; doi:10.3390/en8065997, ISSN 1996-1073, 2015
Flow characteristics in coastal regions are strongly influenced by the topography of the seabed and understanding the fluid dynamics is necessary before installation of tidal stream turbines (TST). In this paper, the bathymetry of a potential TST deployment site is used in the development of a CFD (Computational Fluid Dynamics) model. The steady state k-ϵ and transient Large Eddy Simulation (LES) turbulence methods are employed and compared. The simulations are conducted with a fixed representation of the ocean surface, i.e., a rigid lid representation. In the vicinity of Horse Rock a study of the pressure difference shows that the small change in height of the water column is negligible, providing confidence in the simulation results. The stream surface method employed to visualise the results has important inherent characteristics that can enhance the visual perception of complex flow structures. The results of all cases are compared with the flow data transect gathered by an Acoustic Doppler Current Profiler (ADCP). It has been understood that the k-ϵ method can predict the flow pattern relatively well near the main features of the domain and the LES model has the ability to simulate some important flow patterns caused by the bathymetry.

89. ZHANG, D., AGGIDIS, G.A., WANG, Y., GU, X., LI, W. & CHEN, Y.: "Wave tank experiments on the power capture of a multi-axis wave energy converter", *Journal of Marine Science and Technology*, *vol. 20*, pp. 520-529, DOI: 10.1007/s00773-015-0306-5, Feb-15

This paper presents a new concept of multi-axis wave energy converter (WEC), which can capture wave energy from multiple directions of motion. It describes the modelling of the multi-axis WEC and presents the results of laboratory experiments on the power capture of the multi-axis WEC in a wave tank subjected to synthesized scaled sea waves. The experiments investigate the influence of parameters such as buoy structure, damping and inertia modification (ballasting) on the hydrodynamic performance. The experimental results indicate that the multi-axis WEC yields very good performance under a variety of wave conditions. It is also demonstrated that, by utilizing more than one direction of motion, the multi-axis WEC proves capable of supplying more power than a single-axis WEC. This work constitutes a preliminary step towards the development of an advanced concept of WEC.

Environmental Interaction

91. ABANADES, J., GREAVES, D. & IGLESIAS, G.: "Coastal defence using wave farms: The role of farm-to-coast distance", *Renewable Energy*, pp. 572-582, 2015
The location of a wave farm and, in particular, its distance to the coast is one of the key aspects in a wave energy project. The effects of the farm on the coast, which can be instrumental in mitigating storm-induced erosion and thus contribute to coastal defence, are sometimes disregarded in selecting its location, possibly due to the inexistence of anad hoc methodology. In this context, the objective of this work is to examine the influence of the farm-to-coast distance through a sensitivity analysis in a case study: Perranporth (UK). The impacts of a wave farm on the beach morphology are examined in four scenarios with different farm-to-coast distances using a high-resolution suite of numerical models. The results show that a wave farm closest to the beach offers the highest degree of coastal protection (up to 20% of beach erosion reduction). The downside of this enhanced coastal protection is that the wave resource available at this location would be slightly smaller (approx. 10%) than in the case of the wave farms further from the coast. More generally, we find that the farm-to-coast distance is a critical variable in determining the effectiveness of a wave farm for coastal defence.

92. ALEXANDROS, A., BUCHAN, A.G., PIGGOTT, M.D., PAIN, C.C., HILL, J. & GOFFIN, M.A.: "Adaptive harr wavelets for the angular discretisation of spectral wave models.", *Journal of Computational Physics*, *vol. 305*, pp. 521-538, DOI: 10.1016/j.jcp.2015.10.046, 2015
A new framework for applying anisotropic angular adaptivity in spectral wave modelling is presented. The angular dimension of the action balance equation is discretised with the use of Haar wavelets, hierarchical piecewise-constant basis functions with compact support, and an adaptive methodology for anisotropically adjusting the resolution of the angular mesh is proposed. This work allows a reduction of computational effort in spectral wave modelling, through a reduction in the degrees of freedom required for a given accuracy, with an automated procedure and minimal cost.

93. ANTONUTTI, R., PEYRARD, C., JOHANNING, L. & INGRAM, D.: "The effects of wind-induced inclination on floating wind turbine dynamics in the time domain.", *Renewable Energy*, *vol. 88*, pp. 83-94, DOI: 10.1016/j.renene.2015.11.020, Apr-16
This study focusses on the coupling effects arising from the changes in the hydrodynamic behaviour of a semi-submersible floating wind turbine when it undergoes large inclinations under wind loading. By means of a range of time-domain simulations, it is shown that both the hull geometric nonlinearity effect and the alteration of viscous hydrodynamic forces can significantly affect the dynamics of a typical floating wind turbine operating in waves at rated conditions. The consequences of said effects for both aligned and misaligned wind and waves are explored. In general terms inclinations are found to increase motions, where the modes that are more affected depend on the relative direction between incident wind and waves. Understanding the sources of aero-hydrodynamic coupling is key to providing sound design and modelling guidelines for the coming generation of floating wind turbines.

94. AVDIS, A., JACOBS, C.T., HILL, J., PIGGOTT, M.D. & GORMAN, G.J.: "Shoreline and bathymetry approximation in mesh generation for tidal renewable simulations.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Due to the fractal nature of the domain geometry in geophysical flow simulations, a completely accurate description of the domain in terms of a computational mesh is frequently deemed infeasible. Shoreline and bathymetry simplification methods are used to remove small scale details in the geometry, particularly in areas away from the region of interest. To that end, a novel method for shoreline and bathymetry simplification is presented. Existing shoreline simplification methods typically remove points if the resultant geometry satisfies particular geometric criteria. Bathymetry is usually simplified using traditional filtering techniques, that remove unwanted Fourier modes. Principal Component Analysis (PCA) has been used in other fields to isolate small-scale structures from larger scale coherent features in a robust way, underpinned by a rigorous but simple mathematical framework. Here we present a method based on principal component analysis aimed towards simplification of shorelines and bathymetry. We present the algorithm in detail and show simplified shorelines and bathymetry in the wider region around the North Sea. Finally, the methods are used in the context of unstructured mesh generation aimed at tidal resource assessment simulations in the coastal regions around the UK.

95. BASTON, S.: "Tidal modelling and environmental impacts.", *The Royal Society - International Scientific Seminar India-UK, Edinburgh, United Kingdom*, Mar-14
Marine Renewable Energy is being developed in the UK for several years now. There are three main areas: offshore wind energy, wave energy and tidal energy. The latest consists on extracting energy from tidal currents, which must be faster than 2 m/s to be exploitable. Orkney Islands, and the Pentland Firth specifically, is the area with higher resource in the UK. In this work a regional model of the Pentland Firth has been developed and several

scenarios with different farms layouts and energy extraction, have been simulated. The model has been validated comparing water level against tidal gauges for the shelf grid and velocities against ACDP data at the Pentland Firth. In general the model reproduces tidal flow characteristics effectibely but velocities are over-predicted by 0.5 m/s in neap tides and up to 1 m/s in spring tides. The main goal of the project is to assess the environmental effects in terms of reduction of the flow velocity and length scale of that impact. So far, the main finding of this work is that fitting the ADCP data to an exponential expression it was found that velocity profiles at the Pentland Firth follow a 1/5th power law instead of the commonly assumed 1/7th, which means less energy than expected closer to the seabed.

96. BASTON, S., WALDMAN, S. & SIDE, J.: "Modelling energy extraction in tidal flows.", *TeraWatt Position Papers*, pp. P75-107, *ISBN: 978-0-9934256-0-8*, 2015
Using hydrodynamic modelling to predict the environmental effects of energy extraction is of crucial importance for tidal energy development. This document explores the state of the art in how tidal energy extraction is represented in such models, and specifically examines the implementation of tidal turbines in the Delft3D (4.0 version) and MIKE 3 (2012 version) software. For that purpose, an assumption of horizontal axis rotating turbines to represent Tidal Energy Convertors (TECs) is made. The TeraWatt project uses regional-scale shallow water models, able to simulate wide areas for lengthy periods of time with an achievable computational effort. This allows the consideration of far field effects, which may be important for understanding the environmental impacts of marine renewables.

97. BENJAMINS, S., HARNOIS, V., SMITH, H.C.M., JOHANNING, L., GREENHILL, L., CARTER, C. & WILSON, B.: "Understanding the potential for marine megafauna entanglement risk from renewable marine energy developments", *Scottish National Heritage Commissioned Report No. 791*, 2014
This report considers the potential entanglement risk to marine megafauna from moored marine renewable energy developments (MRE). Existing information relating to entanglement is reviewed, and a qualitative risk assessment was developed to assess relative risk to marine megafauna on the basis of biological (body size, manoeuvrability etc.) and physical (mooring characteristics) risk factors. Results suggest that MRE device moorings are unlikely to pose a major threat, but that some mooring designs pose a greater relative risk than others. Recommendations are made to assist developers include relevant information in their development applications.

98. BRANSCOMBE, T.L., BELL, M.C., MAINLAND, I. & WANT, A.: "Shell biometrics in archaeological and present day limpet samples from around Orkney", *Archaeo and Malacology Group Newsletter, issue. 24*, Apr-14
The coastal locations of virtually all of the archaeological sites on Orkney mean that shell is commonly found throughout them, especially in midden and floor contexts. In many of Orkney's archaeological sites the sandy soil gives a high pH (the soil is alkaline) which also lends to good preservation of these shells so that many of them are complete and measurable samples. Limpet shells are commonly accepted to change in shape according to environmental factors (both at different sites and shore levels) such as wave action, in order to reduce the drag the waves produce in travelling over them. Due to these variations, limpet shells can be useful when looking at archaeological sites as they can be used in relating the archaeological samples to modern sites and therefore showing which beaches (and in some cases even the shore level on the beach) they were being collected from by the people inhabiting the sites at the time. They can also be used to find possible patterns of size selection by ancient gatherers as well as detecting differences between samples from different archaeological eras. In this investigation, primary evidence was collected to attempt to look further into these possibilities and gauge whether these techniques would be applicable to the archaeological limpet samples on Orkney. In the following report, the findings will be presented under two broad topics; the relation of archaeological samples to present day populations and evidence of size selection by gatherers. The archaeological eras involved in this project are the late Iron Age, represented by samples from contexts at The Cairns and Mine Howe, and the Viking Age represented by contexts at Snusgar.

99. BRENNAN, G., KREGTING, L., BEATTY, G.E., COLE, C., ELSÄßER, B., SAVIDGE, G. & PROVAN, J.: "Understanding macroalgal dispersal in a complex hydrodynamic environment: a combined population genetic and physical modelling approach", *Journal of the Royal Society Interface*, *vol. 11*, 2014
Gene flow in macroalgal populations can be strongly influenced by spore or gamete dispersal. This, in turn, is influenced by a convolution of the effects of current flow and specific plant reproductive strategies. Although several studies have demonstrated genetic variability in macroalgal populations over a wide range of spatial scales, the associated current data have generally been poorly resolved spatially and temporally. In this study, we used a combination of population genetic analyses and high-resolution hydrodynamic modelling to investigate potential connectivity between populations of the kelp Laminaria digitata in the Strangford Narrows, a narrow channel characterized by strong currents linking the large semi-enclosed sea lough, Strangford Lough, to the Irish Sea. Levels of genetic structuring based on six microsatellite markers were very low, indicating high levels of gene flow and a pattern of isolation-by-distance, where populations are more likely to exchange migrants with geographically

proximal populations, but with occasional long-distance dispersal. This was confirmed by the particle tracking model, which showed that, while the majority of spores settle near the release site, there is potential for dispersal over several kilometres. This combined population genetic and modelling approach suggests that the complex hydrodynamic environment at the entrance to Strangford Lough can facilitate dispersal on a scale exceeding that proposed for L. digitata in particular, and the majority of macroalgae in general. The study demonstrates the potential of integrated physical-biological approaches for the prediction of ecological changes resulting from factors such as anthropogenically induced coastal zone changes.

100. BRICHENO, L., WOLF, J. & ALDRIDGE, J.: "Distribution of natural disturbance due to wave and tidal bed currents around the UK.", *Continental Shelf Research*, *vol. 109*, pp. 67-77, DOI: 10.1016/j.csr.2015.09.013, 2015
The UK continental shelf experiences large tidal ranges and winter storm events, which can both generate strong near-bed currents. The regular tidal bottom currents from tides plus wind driven 'benthic storms' (dominated by wave-driven oscillatory currents in shallow water) are a major source of disturbance to benthic communities, particularly in shallow waters. We aim to identify and map the relative impact of the tides and storm events on the shallower parts of the North West European continental shelf. A 10-year simulation of waves, tides and surges on the continental shelf was performed. The shelf model was validated against current meter observations and the Centre for Environmental, Fisheries and Aquaculture Science (CEFAS) network of SmartBuoys. Next, the model performance was assessed against seabed lander data from two sites in the Southern North Sea; one in deep water and another shallow water site at Sea Palling, and a third in Liverpool Bay. Both waves and currents are well simulated at the offshore Southern North Sea site. A large storm event was also well captured, though the model tends to underpredict bottom orbital velocity. Poorer results were achieved at the Sea Palling site, thought to be due to an overly deep model water depth, and missing wave–current interactions. In Liverpool Bay tides were well modelled and good correlations (average R2=0.89) are observed for significant wave height, with acceptable values (average R2=0.79) for bottom orbital velocity. Using the full 10-year dataset, return periods can be calculated for extreme waves and currents. Mapping these return periods presents a spatial picture of extreme bed disturbance, highlighting the importance of rare wave disturbances (e.g. with a return period of 1 in 10 years). Annual maximum currents change little in their magnitude and distribution from year to year, with mean speeds around 0.04 ms-1, and maximums exceeding 3 ms-1. Wave conditions however are widely variable throughout the year, depending largely on storm events. Typical significant wave heights (Hs) lie between 0.5 and 2 m, but storm events in shallow water can bring with them large waves of 5 m and above and up to 18 m in North West Approaches/North West Scotland (Sterl and Caires, 2005). The benthic disturbance generated by waves and currents is then estimated by calculating the combined force on an idealised object at the bed. The patterns of this disturbance reflect both regular tidal disturbance and rare wave events. Mean forces are typically 0.05–0.1 N, and are seen largely in areas of fast currents (View the MathML source). The pattern of maximum force however is more dependent on water depth and exposure to long-fetches (View the MathML source) suggesting that it is dominated by wave events.

101. BROUDIC, M., CROFT, T.N., WILLIS, M.R., MASTERS, I. & CHEONG, S.H.: "Long Term Monitoring of Underwater Noise at a Proposed Deployment Site of a Tidal Stream Device", *Fourth International Conference on Ocean Energy (ICOE), Dublin, Ireland*, 17-19 Oct 2012
Tidal streams provide a sustainable, green and predictable energy resource. However, devices designed to extract this energy have the potential to impact upon the natural environment through a variety of interactions. One of these interactions concerns underwater noise. The potential for environmental impact due to device related noise has not been fully understood. Before assessing device related noise disturbance on marine life, it is essential to analyse the mechanics of ambient noise at the high energy sites where devices are likely to be deployed. This paper focuses on a high energy flow channel subject to tidal streams of up to 4 ms-1. Using the "drifting methodology", underwater background noise has been monitored through tidal cycles of different seasons and tides. Analysis shows that this site is subject to biologic, physical and anthropogenic noise sources that contribute differently, and for some periodically, to the overall ambient noise. A distinct increase of 30 dB re1Parms above 8 kHz during spring tide has also been observed and is investigated. The paper shows the relationship between current velocities, the tidal height and the background noise at different times of the year. This will be useful when evaluating the impact of noise on marine life.

102. BROWN, S., GREAVES, D., MAGAR, V. & CONLEY, D.: "Evaluation of turbulence closure models under spilling and plunging breakers in the surf zone", *Coastal Engineering*, DOI: 10.1016/j.coastaleng.2016.04.002, 2016
Turbulence closure models are evaluated for application to spilling and plunging breakers in the surf zone using open source computational fluid dynamics software. A new library of turbulence models for application to multiphase flows has been developed and is assessed for numerical efficiency and accuracy by comparing against existing laboratory data for surface elevation, velocity and turbulent kinetic energy profiles. Out of the models

considered, it was found that, overall, the best model is the nonlinear k - ϵ model. The model is also shown to exhibit different turbulent characteristics between the different breaker types, consistent with experimental data.

103. CARL SEQUEIRA: "Unsteady Gust Response of Tidal Stream Turbines", *IEE Oceans 2014, St Johns, Newfoundland*, pp. 1-10, DOI: 10.1109/OCEANS.2014.7003026, 14-19 Sept 2014
This paper investigates the limitations of 2D linear unsteady aerofoil theory for modelling the unsteady gust response of tidal stream turbines. The work is motivated by the fact that accurate unsteady load prediction is required to determine turbine life. Current state of the art design codes in industry use a single model, based on Theodorsen's theory, to predict the response to all types of gust. This paper shows that different types of gust require different types of model. Vortical gusts, such as due to turbulence and shear flows, should be modelled using a combination of Sears' and Horlock's theories. Pressure gusts, such as those caused by free surface waves, should be modelled using Loewy's theory. The accuracy of these models is examined using numerical predictions. It is shown that, for pressure gusts, using Theodorsen's theory can cause errors in prediction of the unsteady lift amplitude by nearly 18%. By using a calibrated version of Loewy's theory this maximum error can be reduced to less than 8%. Similarly, using the combined Sears/Horlock theory can reduce the error in predicting the response of high frequency vortical gusts from 18% to nearly 10%. The range of gusts likely to occur at real tidal sites is also examined. This has suggested that, in most likely situations, pressure gusts cause variations in loads which can be modelled quasi-steadily, but vortical gusts must be modelled using the combined Sears/Horlock theory.

104. CHATZIRODOU, A. & KARUNARATHNA, H.: "Impacts of tidal energy extraction on sea bed morphology", *10th Young Coastal Scientists and Engineers Conference, Cardiff, United Kingdom*, 2014
In this paper, the application of a 3D numerical model covering the area of Pentland Firth channel (Scotland, UK) to investigate the hydrodynamics related to tidal energy extraction is presented in detail. A full validation analysis is carried out so that the fully operational 3D hydrodynamic model could be applied with confidence in order to explore possible impacts of tidal devices on the ambient marine environment. Following that, a higher resolution hydrodynamic and morphodynamic model covering the area of Inner Sound channel, between the Island of Stroma and Scottish Mainland, favoured for tidal energy extraction inside Pentland Firth, is set up. Preliminary results indicate that the existing morphodynamics of the observed sandbank areas inside Inner Sound Channel are very dynamic. In such a dynamic environment, results imply that possible alterations in tidal currents due to energy extraction may have some implications on the existing morphodynamic regime.

105. CHATZIRODOU, A. & KARUNARATHNA, H.: "Modelling the morphodynamic response of subtidal sandbanks to tidal energy extraction.", *IMA International Conference on Flood Risk, Swansea, United Kingdom.*, 2015
The main objective of the present study is to investigate the morphodynamic response of sub tidal sandbanks to tidal energy extraction. The Inner Sound sub - channel inside Pentland Firth Channel (Scotland, UK), between Scottish Mainland (UK) and the island of Stroma, is used as the test site. The open source Delft3D flow model is used. Time varying water level time-series of a regional Pentland Firth model provided the boundary conditions for a high resolution local scale model of the Inner Sound channel, an area favoured for in-stream tidal turbines deployment. Investigation of the sandbank dynamics during two spring-neap tidal cycles, in a ‘no-energy’ extraction scenario, showed that they are dynamic. It is found that the peak transient currents in circulation can reasonably explain the dominant sediment processes on sandbank features. The impacts of in stream tidal turbines on sea bed dynamics have been further investigated. Horizontal axis turbines were added in a multiple-row configuration and a range of energy extraction scenarios was selected and modelled to map the relationships between the altered current patterns and morphodynamic changes.

106. CHATZIRODOU, A. & KARUNARATHNA, H.: "Modelling the response of subtidal sandbank dynamics to tidal energy extraction.", *IAHR Congress, Hague, The Netherlands.*, 2015
The UK holds a leading position in the emerging marine renewable energy road-map. Marine renewable energy industry is now moving towards deployment of arrays of tidal devices. Prior to consider large scale installations, it is important to investigate environmental impacts associated with tidal energy extraction (Shields et al., 2009). The main objective of the present study is to investigate the morphodynamic response of sub tidal sandbanks to tidal energy extraction. The Inner Sound strait inside Pentland Firth (PF) Channel (Scotland, UK), between Scottish Mainland (UK) and the island of Stroma, is used as the test site. Concerning sea bed morphology, a large sandbank located eastwards and a smaller scale shelf bank area located westwards in the lee of the Island of Stroma, in Inner Sound channel are of particular interest. Open source Delft3D flow model is used. Hydrodynamics of a regional (PF) model provided the boundary conditions for a high resolution local scale model in the Inner Sound sub channel, an area favoured for tidal turbines deployment (Goddijn-Murphy et al., 2013). Investigation of the sandbank dynamics during two spring-neap tidal cycles, at ‘no-energy’ extraction scenario, showed that they are highly dynamic. It is found that the observed tidal asymmetry along with the less significant secondary flows due to the curvature of the flow mainly contribute to the maintenance mechanisms of the sandbanks. Following that, the

current model set up was used to investigate the impacts of tidal current turbines on sea bed dynamics. A range of energy extraction scenarios and array configurations was selected and modelled to map notable relationships between the altered currents and seabed changes.

107. CHATZIRODOU, A. & KARUNARATHNA, H.: "Numerical modelling of sea bed morphodynamics associated with tidal energy extraction", *3rd Oxford Tidal Energy Workshop, Oxford, United Kingdom*, 7-8 April 2014
Tidal energy generation is an option favoured by the UK Government towards its initiative to generate renewable energy. Since the industry is now moving toward - tidal array devices deployments, it is important to investigate environmental impacts associated with tidal energy extraction. As a result, it is essential that a good understanding is gained upon altered residual flows connected to sediment transport regime and perturbed vertical velocity profiles controlling sediments in suspension, and effects of tidal array installations on sea bed sedimentary features, before reaching commercialization [1]. In the present study Delft3D coastal area morphodynamic modelling suite is used to investigate hydrodynamic and in subsequent morphodynamic aspects of tidal energy extraction. Initial results indicate that morphodynamics in areas considered for tidal turbines deployment are in a dynamic equilibrium. In such a dynamic environment, results imply that possible alterations in tidal currents due to energy extraction may have some implications on existing morphodynamic regime.

108. CHATZIRODOU, A., KARUNARATHNA, H. & REEVE, D.E.: "Investigation of deep sea shelf sandbank dynamics driven by highly energetic tidal flows", *Marine Geology*, 22-Apr-16
In this paper we describe a numerical modelling study carried out to investigate the prevailing sediment dynamics of two large sandbanks located at a site designated for future development of tidal stream energy extraction, in the Inner Sound Channel of Pentland Firth, Scotland, UK. A calibrated and validated 3D Delft3D hydrodynamic model covering Pentland Firth channel was combined with a morphodynamic model. The sea bed changes occurring around the sandbanks during a period of two spring-neap tidal cycles are described and discussed in detail. It was found that both sandbanks, which are located in a deep shelf region (depths > 18 m), are morphodynamically active and their existence and integrity are strongly linked with the existing hydrodynamic regime.

109. CROFT, T.N., MASTERS, I. & LAKE, T.: "Methods for Individual Based Modelling of Harbour Porpoise", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Individual Based Models (IBMs) can be used to investigate emergent behaviours of groups and flocks of animals. Early uses of IBMs showed plausible looking behaviours emerging from simple rules and were used in computer generated animations and images. This type of model has since seen use simulating behaviours of a range of animals ranging from clam larvae to moose in a range of environments. The flexibility of the model allows a range of environmental parameters to be included, allowing the response of the simulated animals to the environment to be investigated. The complexity of these models can vary considerably, and a number of additions can be made to the basic IBM structure. The detail and complexity of these models is in part constrained by the availability of environmental data and in part by available data of the animals to be simulated, which can be particularly difficult to obtain in a marine environment. A planned model for the behaviour of Harbour Porpoise (Phocoena phocoena) is given as an example use of these techniques.

110. CULLEY, D.M., FUNKE, S.F., KRAMER, S.C. & PIGGOTT, M.D.: "A hierarchy of approaches for the optimal design of tidal turbine arrays.", *ICOE conference, Halifax, Canada*, 2014
From conception to construction, the process by which tidal turbine farms are scoped and designed (and even optimised – which is the focus here) is multi-layered. The industrial designer requires tools of varying fidelities working on multiple scales, depending on the task at hand. In this paper a hierarchy of modelling approaches is proposed and some examples demonstrated. For site-scoping and resource assessment, the continuum approach enables multiple farms to be considered and optimised over a large geographic area. This is demonstrated for four farms in the Pentland Firth, Scotland. For detailed design, three-dimensional CFD codes allow flow around a turbine to be fully resolved and the physical processes closely modelled. In between, and informed by these extremes, are array design tools whereby each turbine is individually represented and the flow over the domain is calculated with the non-linear shallow water equations. In a test example, the positions of 78 turbines in a farm located in the Inner Sound of the Pentland Firth, Scotland is optimised with a resulting 25% improvement in power extracted. A holistic approach to the design process is also presented which seeks to design with the maximisation of developer’s profit – rather than power extracted - as the ultimate goal.

111. CULLEY, D.M., FUNKE, S.W., KRAMER, S.C. & PIGGOTT, M.D.: "Tidal stream resource assessment through optimisation of array design with quantification of uncertainty.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
As the number of tidal stream turbines within an array increases, so the effects of that array on the flow and environment accumulate. Many key objective measures (such as energy yield or financial profit) begin to suffer the

effects of diminishing increases. Optimising the layout of individual turbines within an array – micro-siting – facilitates significantly increased energy harvest for a given number of turbines in a given area, as compared to a 'human's best attempt' design. The optimal micro-siting design of an array, and therefore an accurate forecast of the yield of that array, must be found as the product of an optimisation exercise which may incorporate turbine parameters, local bathymetry and a host of other practical, physical, legal, financial or environmental constraints. The number of turbines within an array proposed for a given site has an even greater effect on the yield of that array. Determining the optimum number of turbines is, therefore, a problem of critical importance. Like the micro-siting design, this also cannot be solved directly but must be approached through a process of iterative optimisation. Consequently, only through determining the optimal number of turbines and their arrangement, can a reliable estimate of the accessible tidal resource on a site be made. Making this determination is, however, computationally intensive. In this paper, tools from statistical decision theory, such as surrogate modelling and variable fidelity sampling, are used to efficiently allocate computational effort where it provides most value in the optimisation of the number of turbines. This enables the array design problem to be tackled much more efficiently than would be possible using more conventional optimisation approaches. Finally, having determined the optimal array design it is imperative that the sensitivity of the design to modelling assumptions can be quantified and fully understood. This paper focuses on a brief exploration of three aspects of resource assessment through array design: Firstly, TidalArraySizer is presented, this is a framework for the optimisation of tidal turbine array size built upon OpenTidalFarm project. Secondly developments are presented which provide OpenTidalFarm with functionality to measure the sensitivity of the objective function with respect to the modelling parameters. Thirdly, these contributions are demonstrated on an example based upon the Inner Sound of the Pentland Firth.

112. DAVIES, I. ET AL: "Towards an understanding of significant alterations in the hydrographic regime.", *Terawatt special issue of the Journal of Ocean and Coastal Management*, 2015
The substantial wave and tidal marine renewable energy (MRE) resources available in Scottish waters have been the subject of considerable interest for commercial exploitation but, so far, little MRE development has taken place beyond demonstration projects. The next phase will see these wave and tidal devices deployed in arrays, with many sites being potentially developed. Much of this development will take place in waters surrounding the Orkney Islands, north of Scotland, where much of the resource is located. This paper summarises the outcomes of a modelling project to develop methodologies for quantifying the changes to the physical environment by large-scale wave and tidal arrays. The overarching objective of the project is to provide a common data and modelling toolbox to industry, academia and regulators to assess the resource and potential individual and cumulative impact of energy extraction, in order to comply with the national and international planning, regulatory and legislative framework. This paper draws on the project outputs and discusses how the methodologies we developed could be used to quantify acceptable thresholds for sustainable MRE exploitation. A number of recommendations on good practice for similar initiatives and directions for further research are also presented.

113. DE JESUS HENRIQUES, T.A., TEDDS, S.C, BOTSARI, A., NAJAFIAN, H., SUTCLIFFE, C.J, OWEN, I. & POOLE, R.J.: "Performance of Horizontal Axis Tidal Turbines under Wave-Current Interactions", *8th World Congress on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics 2013, Lisbon, Portugal*, 16-20 June 2013
An experimental investigation has been performed using the high-speed re-circulating water channel at the University of Liverpool combined with a paddle wavemaker installed upstream of the working section to produce wave-current flow. A wide range of regular linear waves were produced in the channel; these were well characterised and found to be reproducible. An Acoustic Doppler Velocimeter was used to measure three-dimensional velocities and turbulent statistics through the water depth for two different waveforms. The measured water particle velocities showed excellent agreement with theoretical results calculated using linear wave theory. For different flow conditions (current alone and wave-current interaction) power and thrust measurements were obtained for a scale-model 0.5m diameter three bladed Horizontal Axis Tidal-Stream Turbine. It was observed that the presence of waves causes a significant cyclic variation in the power and thrust but the mean coefficients of power and thrust in the unsteady (wave-current) flow conditions were very similar to those obtained in steady flow.

114. DE JESUS HENRIQUES, T.A., TEDDS, S.C., BOTSARI, A., NAJAFIAN, H., HEDGES, T.S., SUTCLIFFE, C.J., OWEN, I. & POOLE, R.J.: "The effects of wave-current interaction on the performance of a model horizontal axis tidal-stream turbine", *International Journal of Marine Energy*, 2014
This experimental study investigates the performance of a marine current turbine in the presence of surface waves. The tests were carried out in the high-speed recirculating water channel at the University of Liverpool. A three blade model of a horizontal axis tidal turbine with a rotor diameter of 0.5m was exposed to water flow with a steady uniform upstream velocity of 0.5m/s. Regular surface waves were generated using a paddle wavemaker capable of producing a wide range of wave conditions in a current dominated flow (i.e. wave-induced velocities lower than current velocity). To determine the fluctuations in the current velocities caused by the surface waves,

an Acoustic Doppler Velocimeter was used to measure the three-dimensional velocity components at various depths beneath two different waveforms. The measured kinematics of the waves showed excellent agreement with linear wave theory. Thrust and power measurements were taken from the turbine under flow conditions with the same two waveforms and compared with results taken in steady uniform flow to evaluate the effect of the wave-induced velocities on the turbine performance. The mean coefficients of power and thrust in the unsteady flow conditions were found to be very similar to those obtained in steady flow, but there were significant cyclic variations in the power and thrust which occurred at the frequency of the waves.

115. DE JESUS HENRIQUES, T.A., TEDDS, S.C., BOTSARI, A., NAJAFIAN, H., SUTCLIFFE, C.J., OWEN, I. & POOLE, R.J.: "The Effects of Wave-Current Interactions on the Performance of a Model Horizontal Axis Tidal-Stream Turbine", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
An experimental investigation into the performance of a horizontal axis tidal stream turbine in the presence of surface waves is presented. The tests were carried out in the high-speed water channel at the University of Liverpool. A three blade model of a HATT with a rotor diameter of 0.5m was used with an upstream water velocity of 0.5m/s. Regular linear waves were produced using a paddle wavemaker which produces a wide range of wave-current flows. An Acoustic Doppler Velocimeter was used to measure three-dimensional velocity components through the water depth below the waves. The streamwise and vertical velocity components showed excellent agreement with linear wave theory. Thrust and power measurements were taken for uniform flow and two waveforms of different wavelength and frequency. It was observed that the presence of waves caused a significant cyclic variation in the power and thrust but the mean coefficients of power and thrust in the unsteady flow conditions were very similar to those obtained in steady flow.

116. DE JESUS HENRIQUES, T.A., TEDDS, S.C., BOTSARI, A., NAJAFIAN, H., SUTCLIFFE, C.J., OWEN, I. & POOLE, R.J.: "The Effects of Wave-Current Interactions on the Performance of a Model Horizontal Axis Tidal-Stream Turbine", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
This project investigates the effects of extreme conditions on marine energy generators when installed as a single device or in arrays or farms. By combining the results of experiments, computer predictions and real life expertise, the research will enable the industry to produce, design and manufacture better tidal stream turbines that can be optimised to suit the prevailing sea conditions. Once these devices are deployed there will be a need to remotely monitor their condition and manage their operation during their life time. This research will deliver a system that will allow the owners of the devices to remotely monitor their condition and performance to ensure they achieve optimal energy production whilst maximising their life span. This will enable the electricity suppliers using this source of renewable energy to achieve the best possible long term economic performance. Finally, the environmental impact of such installations will be considered to ensure the positioning of these devices is not detrimental to the surrounding sea, coast and seabed.

117. EVANS, P., ARMSTRONG, S., WILSON, C., FAIRLEY, I., WOOLDRIDGE, C. & MASTERS, I.: "Characterisation of a highly energetic tidal energy site with specific reference to hydrodynamics and bathymetry", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Characterisation of a tidal energy site must include the interrelationships between flow and bathymetry so that impacts can be anticipated with a high level of detail and confidence. This paper presents high-spatial resolution velocity data of tidal flow, which was measured using a vessel-mounted acoustic Doppler current profiler (ADCP) within Ramsey Sound, Wales. This is a high energy environment where peak mean current speeds during spring tides are in excess of 4ms -1. The spatial variability of the flow, both transversely and vertically, in this area is high, with the flood and ebb tides displaying markedly different regimes. The vertical shear across the swept width of a 15m diameter TST has revealed that the shear at lower velocities (namely during the ebb tide) is relatively low, however, the vertical shear increases with increasing velocity and in many locations along the deeper channel where the velocity magnitude is high enough for energy extraction, the vertical shear is very high. A selection of locations are identified where the average velocity across the turbine is high and the vertical shear is relatively low, however, these areas are adjacent to areas of high vertical shear in the deep channel. Vertical shear during peak flood conditions is greatest immediately upstream and downstream of a prominent pinnacle. This paper demonstrates that small-scale and large-scale bathymetric features have a major influence on velocity structure, and can significantly alter the principal flow direction.

118. FAIRLEY, I. & KARUNARATHNA, H.: "Morpodynamics in the lee of wave energy converter arrays", Proc. 2nd Int. Conf. on Environmental Interactions of Marine Renewable Technologies, Stornoway, Isle of Lewis, Scotland, United Kingdom, vol. 51, pp. 354-361, 28 April - 2 May 2014
A fully coupled 3D spectral wave, hydrodynamic and sand transport model is used to investigate the impact of wave energy converters on the Bay of Skaill, Orkney. Cross-shore intertidal beach profiles were measured over a short term experiment to provide calibration data for the numerical model. The model failed to correctly predict

the measured intertidal change. Tests with wave energy converters in place did show differences in beach response but confidence in results is low due to poor predictability of the natural condition.

119. FAIRLEY, I. & KARUNARATHNA, H.: "The cumulative impacts of tidal stream turbine arrays on sediment transport in the Pentland Firth", *Renewable Energy*, *vol. 80*, pp. 755-769, DOI: 10.1016/j.renene.2015.03.004, Aug15
This contribution investigates the impact of the deployment of tidal stream turbine arrays on sediment dynamics and seabed morphology in the Pentland Firth, Scotland. The Pentland Firth is arguably the premier tidal stream site in the world and engineering developments are progressing rapidly. Therefore understanding and minimising impacts is vital to ensure the successful development of this nascent industry. Here a 3 dimensional coupled hydrodynamic and sediment transport numerical model is used to investigate the impact on sediment transport and morphodynamics of tidal stream arrays. The aim of the work presented here is twofold: firstly to provide prediction of the changes caused by multiple tidal stream turbine array developments to some of the unique sandy seabed environments in the Pentland Firth and secondly as a case study to determine the relationship between impacts of individual tidal stream farms and cumulative impacts of multiple farms. Due to connectivity in tidal flow it has been hypothesized that the cumulative impact of multiple arrays on sediment dynamics might be non-linear. This work suggests that, for the Pentland Firth, this is not the case: the cumulative impact of the 4 currently proposed arrays in the area is equal to the sum of the impacts of the individual arrays. Additionally, array implementation only has minimal effect on the baseline morphodynamics of the large sandbanks in the region, smaller more local sandbanks were not considered. These two results are extremely positive for tidal stream developers in the region since it removes the burden of assessing cumulative impact from individual developers and suggests that impacts to sub-sea morphodynamics is insignificant and hence is unlikely to be an impediment to development in the Pentland Firth with the currently proposed levels of extraction.

120. FAIRLEY, I. & KARUNARATHNA, H.: "Modelling the impacts of marine energy extraction on non-cohesive sediment transport and morphodynamics", *TeraWatt Position Papers*, pp. 109-129, *ISBN: 978-0-9934256-0-8*, 2015
This report summarises the methodologies and philosophies used within the Terawatt Project to study the impact of marine energy extraction on non-cohesive sediment dynamics using examples from the Pentland Firth and Orkney Waters. The actual extraction of energy and hydrodynamic modelling methodologies are comprehensively dealt with in the relevant Terawatt position papers and hence aspects relating solely to sediment transport are focused on. Certain hydrodynamic aspects are discussed, however, due to their importance to sediment transport. It must be emphasized that without accurate simulation of hydrodynamic and wave parameters morphodynamic predictions will necessarily be inaccurate. Rather than only discuss modelling techniques, much of this report discusses the preparation of input data. Of primary importance is access to spatially varying data on sediment size and spatial distribution, and the methodologies for deriving information in the face of limited data is presented. It is the opinion of the Terawatt consortium that for areas such as the Pentland Firth, adequate spatial representation should be prioritised over absolute data quality. Calibration data for both the wave and tidal forcing and, ideally the morphodynamic change is also important. Wave and tidal scenarios are considered together because there are some common themes that run between both technology types. For many wave deployment areas, pragmatism is required: high energy, wave exposed environments often have limited mobile sediment between hard rock geology and in such situations not only is the likelihood of accurate predictions low, but the severity of impact likely to be minimal as well. Therefore, one can rely on conceptual models to suggest likely changes rather than numerical coastal models. Pragmatism is also required with regards the balance between mesh size and resolution and computational expense.

121. FAIRLEY, I., BROUDIC, M., MALKI, R., HORSFALL, I. & MASTERS, I.: "Results from a multi-disciplinary survey campaign at a tidal stream site in west Wales", *ENSUS 2011, Newcastle University, UK*, 2011
Welsh Assembly Government has ambitions to use marine renewable energy to provide a significant percentage of Wales's electricity requirements. One method of extracting renewable energy from the marine environment is to harness the energy from tidal currents. This energy, termed tidal stream energy, can only be extracted in areas where currents are sufficiently high, such as through channels or around headlands. Wales has an excellent tidal stream resource, primarily in Pembrokeshire, Anglesey and the Bristol Channel. Ramsey Sound, Pembrokeshire is the location where Wales's first tidal stream device will be deployed. Tidal Energy Ltd. has consent for a one year demonstration of their Deltastream device in the sound. Equally, it is believed that the area to the West of Ramsey Island is likely to hold tidal stream arrays in the future. This area is not only a tidal stream hot spot, but also an area of high touristic value and a marine special area of conservation with a variety of protected species, including grey seals and harbour porpoise. Therefore it is important to understand the baseline conditions in these areas so that any possible future changes caused by tidal stream turbines can be determined. The data is also necessary to calibrate and validate numerical models which can be used to test the impacts of tidal stream turbines. Over a two week neap-spring cycle in May 2011, several Welsh universities worked on two research vessels and undertook a

multi-disciplinary survey campaign in the Ramsey Sound area. Transects of current measurement were conducted using acoustic doppler current profilers which allows for further understanding of the tidal resource in the area and the variation of currents around complex bathymetry. Ambient underwater noise and noise propagation measurements were taken using a hydrophone from a small RIB. Understanding of background noise and noise propagation is important to determine whether any additional noise generated by turbines will affect the local wildlife. The current patterns and noise data can be combined to develop predictive models of noise propagation and hence any turbine impact. Understanding of the marine biology in the area was enhanced by echo-sounding of pelagic fish behaviour and observations of marine mammal behaviour. Combining understanding of tidal currents with the behavioural characteristics of marine wildlife will enable greater understanding of how fish and mammal behave around natural structures in high tidal flows and hence extrapolation to how they may behave around man-made structures.

122. FAIRLEY, I., CHATZIRODOU, A. & KARUNARATHNA, H.: "Effects of marine energy extraction on non-cohesive sediment transport and morphological change in the Pentland Firth and Orkney Waters.", *Terawatt special issue of the Journal of Ocean and Coastal Management*, 2015
This paper considers the process of modelling sediment transport and morphological change in the Pentland Firth and Orkney Waters using coastal area models. This region is atypical of regions commonly modelled using such techniques: it is high energy with limited and highly variable regions of mobile sediment. This causes challenges with regards both model capability and availability of data. Computational time restrictions for fully coupled modelling solutions should also be recognised which limits practical duration of simulation. Impacts to modelled bed level change over test periods are noted for both wave and tidal energy extraction scenarios. In both cases the magnitude of difference is equal to the magnitude of the change itself, however lack of data and poor validation of the morphological modelling for the wave energy test case means confidence is low in these results. Based on the difficulties faced in conducting these modelling exercises and the high cost of additional data collection, it is recommended that regulators take a pragmatic approach when requiring such modelling for environmental impact assessments at some locations where changes to morphodynamics are unlikely to be critical to key receptors. Other approaches such as conceptual modelling or consideration of bed shear stresses could be undertaken rather than fully coupled morphodynamic modelling.

123. FAIRLEY, I., KARUNARATHNA, H. & MASTERS, I.: "Sediment transport in the Pentland Firth and impacts of tidal stream energy extraction.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
This paper presents an analysis of the difference to residual sediment transport pathways and bed level changes forced by the installation of four tidal stream turbine arrays in the Pentland Firth. Two areas are considered in detail: the Sandy Riddle, a large banner bank and a sandbank in the Inner Sound close to the Meygen development. No noticeable differences are found for the Sandy Riddle at the modelled level of extraction, residual pathways are the same and the difference in bed level change between the two scenarios is at most 3% of the total modelled change. Greater differences are noted for the Inner Sound case, but uncertainties in sediment coverage and mesh effects in this area mean confidence is lower in these results.

124. FAIRLEY, I., MASTERS, I. & KARUNARATHNA, H.: “The cumulative impact of tidal stream turbine arrays on sediment transport in the Pentland Firth”, *Renewable Energy, vol. 80*, pp. 755-769, doi: 10.1016/j.renene.2015.03.004, 201
This contribution investigates the impact of the deployment of tidal stream turbine arrays on sediment dynamics and seabed morphology in the Pentland Firth, Scotland. The Pentland Firth is arguably the premier tidal stream site in the world and engineering developments are progressing rapidly. Therefore understanding and minimising impacts is vital to ensure the successful development of this nascent industry. Here a 3 dimensional coupled hydrodynamic and sediment transport numerical model is used to investigate the impact on sediment transport and morphodynamics of tidal stream arrays. The aim of the work presented here is twofold: firstly to provide prediction of the changes caused by multiple tidal stream turbine array developments to some of the unique sandy seabed environments in the Pentland Firth and secondly as a case study to determine the relationship between impacts of individual tidal stream farms and cumulative impacts of multiple farms. Due to connectivity in tidal flow it has been hypothesized that the cumulative impact of multiple arrays on sediment dynamics might be non-linear. This work suggests that, for the Pentland Firth, this is not the case: the cumulative impact of the 4 currently proposed arrays in the area is equal to the sum of the impacts of the individual arrays. Additionally, array implementation only has minimal effect on the baseline morphodynamics of the large sandbanks in the region, smaller more local sandbanks were not considered. These two results are extremely positive for tidal stream developers in the region since it removes the burden of assessing cumulative impact from individual developers and suggests that impacts to sub-sea morphodynamics is insignificant and hence is unlikely to be an impediment to development in the Pentland Firth with the currently proposed levels of extraction.

125. GARRETT, J.K., WITT, M.J. & JOHANNING, L.: "Long term underwater third octave sound levels at a busy UK port.", *2nd International Conference and Exhibition on Underwater Acoustics, Rhodes, Greece*, 22-27 June
The sound levels of the third octave bands with centre frequency 63 Hz and 125 Hz will be used as indicators for the EU Marine Strategy Framework Directive (MSFD) descriptor 11 to monitor low frequency continuous sound in the marine environment. To explore this, long term underwater sound data from a busy UK port were investigated. Two autonomous multichannel acoustic recorders (AMAR Generation 2; Jasco Applied Sciences) recording broadband sound in the effective frequency range 10 Hz to 32 or 48 kHz, for half an hour in every hour, have been deployed alternately at the Falmouth Bay Test site for marine renewable energy devices (FaBTest) off the south coast of Cornwall, UK from March 2012 to August 2013. Data collected during periods of wave energy device testing were removed for this analysis. The area supports considerable commercial shipping and recreational boating along with diverse marine fauna, including bottlenose dolphins, harbour porpoises and fish. Custom MATLAB scripts were used to derive third octave levels (TOLs). The mean half hourly TOLs were found to vary by season with a mean TOL for the 63 Hz band increasing from 87.88 dB re 1 µPa in July 2012 to a mean of 98.10 dB re 1 µPa for December 2012. The yearly mean TOLs of 92.39 ± 8.45 dB re 1 µPa and 95.14± 6.61 dB re 1 µPa for the 63 and 125 Hz bands respectively (number of half hour sound files = 6992) were below the suggested target of 100 dB re 1 µPa for the period March 2012-March 2013. This provides information on the current sound levels from which a trend can be monitored at this site. The empirical data presented here offers an exploration of the proposed MSFD indicator bands in order to inform future use.

126. GODDIJN-MURPHY, L.M.,WOOLF, D.K. & EASTON, M.C.: "Current patterns in the Inner Sound (Pentland Firth) from underway ADCP data", *Journal of Atmospheric and Oceanic Technology*, *vol. 30*, pp. 96-111, DOI: 10.1175/JTECH-D-11-00223.1, 2013
Numerous acoustic Doppler current profiler (ADCP) surveys were performed in the Inner Sound of the Pentland Firth, a channel between the Orkney Islands and the northern coast of Scotland connecting the Atlantic Ocean to the west and the North Sea to the east. The Pentland Firth has the highest tidal streams of the British Isles, and one of the highest that can be found around the globe. Here, the tidal energy industry is in its demonstration phase, but not many real current measurements are in the public domain. The authors present real current data, measured during different phases of the tidal cycle, using a vessel-mounted ADCP. The tidal changes can be rapid, and because the underway measurements take time, the apparent spatial patterns are affected by temporal variation. A method is described that estimated and corrected this temporal distortion using a hydrodynamic model. It appeared that ebb and flood streams did not fully overlap, and that the tidal streams were more complicated, turbulent, and variable than existing models suggest. The data were analyzed for characteristics pertinent to practical tidal stream energy exploitation, and two favorable sites in the Inner Sound are identified. All original current data are available from the British Oceanographic Data Centre (BODC).

127. GOWARD BROWN, A.J. & NEILL, S.P.: "3D ROMS modelling of the Pentland Firth – a world-leading tidal energy resource", *TOS/ASLO/AGU Ocean Sciences meeting, Honolulu, Hawaii*, 23-28 Feb 2014
The Pentland Firth is a highly energetic tidal strait situated in the north of Scotland and a key location for tidal energy exploitation. Bathymetric and topographic complexities within the Pentland Firth will alter the vertical velocity structure and turbulence properties as the tide flows through the strait. Since observations in such energetic environments are difficult, we here apply the 3D ROMS model to the Pentland Firth in order to resolve uncertainties within tidal energy resource assessment. The tidal velocities during the flood and ebb phases of the tide are influenced by the islands and sub-channels within the Pentland Firth. Using the ROMS model, it is possible to determine the extent to which the tidal resource varies temporally and spatially, and clarifies how the vertical and horizontal velocity fields interact. Accurately modelling the tidal dynamics within this environment ensures that potential consequences of tidal energy extraction on the surrounding environment are better understood.

128. GOWARD BROWN, A.J., NEILL, S.P. & LEWIS, M.J.: "Impact of wind variability on marine current turbines", *2nd Oxford Tidal Energy Workshop (OTE 2013), Department of Engineering Science, University of Oxford*, pp. 47-48, 18-19 March 2013
An important aspect of marine current turbine technologies that has not yet been fully addressed is an understanding of the loading mechanism and hydrodynamics on and around tidal devices in realistic oceanic environments. Winds exhibit high spatial and temporal variability that wave models, typically forced with a 3 hourly wind input, do not resolve. Subsequently, the impact that surface waves may have on marine current turbine structures may be underestimated. To determine the environmental impacts of marine current turbines and to make accurate resource estimates, realistic simulations which include waves may be required. Using the SWAN wave model, the extent that fluctuating wind affects wave height and period has been examined. Both wave height and wave period can be altered as a result of high frequency wind input. Consequently, understanding and simulating the impact of wind variability on wave properties can determine the extent of wave effects on marine current turbine extreme and fatigue loading.

129. GOWARD BROWN, A.J., NEILL, S.P. & LEWIS, M.J.: "The influence of wind variability on estimating the wave power resource", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Wave models are typically forced with synoptic wind fields at 3 hourly intervals. In reality, winds are highly turbulent and exhibit high spatial and temporal variability. Therefore, using 3 hourly wind fields to force wave models, the extent of the natural variability may be masked. Subsequently, the impact on generating surface waves may be underestimated. Until now research has been focused upon the effect of spatial resolution within hydrodynamic models with little research focusing on the effect of temporal resolution. Here, an idealised storm event, within a model domain of similar dimensions to the North Sea, is simulated using the SWAN wave model. The extent that fluctuating wind affects wave power has been examined, with a test case where wind, without additional gustiness, was input as the control. The results indicate that the inclusion of wind variability at sub hourly time-steps is likely to affect estimates of the wave power resource. Wave power is a function of the wave period and the square of wave height, both of which can be altered as a result of high frequency wind input. Consequently, understanding and accurately simulating the impact of wind variability on wave properties can improve the accuracy of wave power predictions.

130. GREAVES, D., CONLEY, D., MAGAGNA, D., AIRES, E., CHAMBEL LEITÃO, J., WITT, M., EMBLING, C.B., GODLEY, B.J., BICKNELL, A., SAULNIER,J-B., SIMAS, T., O'HAGAN, A.M., O'CALLAGHAN, J., HOLMES, B., SUNDBERG, J., TORRE-ENCISO,Y., & MARINA, D.: "Environmental Impact Assessment: gathering experience at wave energy test centres in Europe", *International Journal of Marine Energy*, DOI: 10.1016/j.ijome.2016.02.003, 2015
From a review of the EIAs performed at wave energy test centres, we identified several lessons regarding the wave energy EIA process. There is clear evidence that the receptors of primary interest are dependent on factors such as the local environmental characteristics, the presence/absence of protected species and the regulatory authority under which the EIA is performed. Furthermore, it is recommended that concerns relating to cumulative impacts, from an expanding level of wave energy development taking place in a background of growing utilisation of the marine environment, which are largely unknown at this early stage of the industry may be comprehensively addressed at the national level as part of a Strategic Environmental Assessment (EIA) and/or in Maritime Spatial Planning (MSP) and that it should be regularly reassessed.

131. GREENWOOD, C.E. & CHRISTIE, D.: "A frequency independent method for the simulation of Disturbances around a small scale wave farm using a Boussinesq simulation.", *International Conference on Environmental Interactions of Marine Renewable Energy Technologies, Stornoway, United Kingdom*, 28 April - 2 May 2014
A Boussinesq model has been created to simulate the presence of an array of shallow water wave surge oscillator devices using DHI's MIKE21 Boussinesq wave (BW) model suite. The simulation uses a regular grid domain with a constant depth of 10m and a grid spacing of 2m in the x and y dimension. This new method provides a crucial enhancement of including a frequency dependant absorption, where the devices reflected, absorbed and transmitted characteristics are shown using a realistic power transfer function. The frequency spectrum as a set of n monochromatic waves at frequency intervals with a proportional energy scaled wave height. A simulation is then run for each frequency where the porosity value is dependent on the WEC's absorption spectrum. The results of each simulation are then summed to form overall wave energy. The results demonstrate the application of this new method and provide a detailed map of the spatial change in wave energy around devices, highlighting the regions of importance.

132. HASHEMI, M.R. & NEILL, S.P.: "The role of tides in shelf-scale simulations of the wave energy resource", *Renewable Energy*, *vol. 69*, pp. 300-310, DOI: 10.1016/j.renene.2014.03.052, 2014
Many regions throughout the world that are suitable for exploitation of the wave energy resource also experience large tidal ranges and associated strong tidal flows. However, tidal effects are not included in the majority of modelling studies which quantify the wave energy resource. This research attempts to quantify the impact of tides on the wave energy resource of the northwest European shelf seas, a region with a significant wave energy resource, and where many wave energy projects are under development. Results of analysis based on linear wave theory, and the application of a non-linear coupled wave-tide model (SWAN–ROMS), suggest that the impact of tides is significant, and can exceed 10% in some regions of strong tidal currents (e.g. headlands). Results also show that the effect of tidal currents on the wave resource is much greater than the contribution of variations in tidal water depth, and that regions which experience lower wave energy (and hence shorter wave periods) are more affected by tides than high wave energy regions. While this research provides general guidelines on the scale of the impact in regions of strong tidal flow, high resolution site-specific coupled wave-tide models are necessary for more detailed analysis.

133. HASHEMI, M.R., NEILL, S.P., DAVIES, A.G. & LEWIS, M.J.: "The implications of wave-tide interactions in marine renewables within the UK shelf seas", *2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR), University of the Highland and Islands, Stornoway, United Kingdom*, 28 April - 2 May 2014

There are many regions throughout the world which concurrently experience a high wave and a high tidal energy resource. These regions include the northwest European shelf seas, the Gulf of Alaska, New Zealand, northwest Australia, and the Atlantic seaboard of Argentina. Due to wave-tidal interactions, special consideration needs to be given to energy schemes developed in such regions. In particular, resource assessments of such regions should account for the way that one marine resource (e.g. waves) modulates other marine resources (e.g. tides) at a variety of timescales. In the present research, a coupled wave-tide model of the NW European shelf seas has been developed using SWAN-ROMS. After model validation at a number of tidal gauges and wave buoys the effect of tides on the wave resource assessment is presented. Results of analysis based on linear wave theory, and the application of a nonlinear coupled wave-tide model, suggest that the impact of tides on waves can be significant in site assessment, and can exceed 10% in some regions. We also conclude that it is the tidal currents, rather than tidal depth variations, that are the main factor at this scale. While a coupled model can theoretically implement many wave-tide interaction processes, the application of the model at shelf scale is highly constrained by computational cost, model resolution and data availability.

134. HEATH, M., SABATINO, A., SERPETTI, N., & O'HARA MURRAY, R.: "Scoping the impact of tidal and wave energy extraction on suspended sediment concentrations and underwater light climate.", *TeraWatt Position Papers*, pp. 143-166, *ISBN: 978-0-9934256-0-8*, 2015
The depth to which sunlight penetrates below the sea surface is one of the key factors determining the species composition and productivity of marine ecosystems. The effects range from the rate and fate of primary production, through the performance of visual predators such as fish, the potential for refuge from predators by migrating to depth, to the scope for seabed stabilisation by algal mats. Light penetration depends partly on spectral absorption by seawater and dissolved substances, but mainly on the scattering caused by suspended particulate material (SPM). Some of this SPM may be of biological origin, but in coastal waters the majority is mineral material originating ultimately from seabed disturbance and land erosion, the latter being deposited in the sea by rivers and aerial processes. SPM is maintained in the water column or deposited on the seabed depending on combinations of hydrodynamic processes including baroclinic (density-driven) or barotropic (mainly tidal and wind driven) currents, and wave action (Ward et al. 1984; Huettel et al. 1996). Since tidal and wave energy extraction must alter these hydrodynamic properties at some scales depending on the nature of the extraction process, we can expect some kind of impact on the concentration of the SPM. If these are large enough, we may have to consider the extent to which these may impact the underwater light environment and the local or regional ecology. Whilst several coupled hydrodynamic-sediment models exist to predict SPM distributions in aquatic systems, their skill level in open coastal and offshore marine waters is acknowledged to be relatively low. This is largely because the processes are not well understood and the formulations are largely based on empirical relationships rather than fundamental physical principles. The models are also highly demanding in terms of calibration data and computational resources. Hence their utility for predicting relatively subtle effects arising from changes in flow or wave environments due to energy extraction devices seems rather low. Here, we summarise the key mathematical functions describing the processes involved in sediment suspension, and propose a lightweight one-dimensional (vertical) model which can be used to scope the effects of changes in flow and wave energy on SPM.

135. HORRILLO-CARABALLO, J.M. & REEVE, D.E.: "Application of a statistical method to investigate patterns of beach evolution in the vicinity of a seawall", *Journal of Coastal Research*, *issue. 64*, pp. 95-99, 2011
In this paper we describe the application of Canonical Correlation Analysis (CCA) to an historical dataset of seabed elevations within a coastal segment of the English south eastern coast. The study site is located along the frontage of Walcott (Norfolk, East coast of England). The beaches along this segment of coast are mainly composite, mixed sand and shingle. The dataset comprises detailed bathymetric surveys of beach profiles covering a period of over 17 years (~ 2 beach profile surveys every year). The structure of the dataset and the data handling methods are described. The application of the CCA method is discussed as well as the ability of the CCA to provide useful forecast of the beach profile at Walcott. Some results and interpretation of the analysis are presented. Beach profiles predictions agreed well with the measured profiles for up to five years of forecast at the site. The level of error using CCA is proportionate with that found with dynamical modelling. It is expected that this relationship will be used by coastal planners to predict profile evolution based on waves and storm surges.

136. HU, Z.Z., GREAVES, D., HANN, M. & IGLESIAS, G.: "Fluid-Structure interaction problems in free-surface flow applications", *3rd PRIMaRE Annual conference. Bath. U.K*, 2016
The aim of the present paper is to build a self-contained multiple fluid flow Fluid Structure Interaction (FSI) module in the open source Computational Fluid Dynamics (CFD) package OpenFOAM (Open Field Operation and Manipulation). At present, the FSI module in OpenFOAM [1] exists only for single fluid flow and it remains a challenge to model the interaction between multiple fluid flows with a free surface and elastic body deformation. In this study, the Finite Volume Method (FVM) is used to model both multiple fluids and structures to simulate

dynamic interaction between an incompressible Newtonian fluid and an elastic solid with the assumption of large structure deformation. Typical applications are in fluid structure interaction problems for offshore wind structures or wave and tidal energy devices subject to wave loads. The laminar Navier-Stokes Equations are solved on a dynamic mesh using the Pressure Implicit with Splitting of Operator (PISO) procedure on the two phase flow. A Volume of Fluid (VoF) interface capturing approach is used to model the free surface. The structure solver applies the second order cell-centred FVM for spatial discretisation of the linear momentum conservation law in the updated Lagrangian formulation. A strong coupling algorithm is used between fluid and structure, which has been derived for a fully nonlinear setting. Finally, the two phase FSI solver is validated on a 3D dam breaking impact on a elastic structure.

137. KARUNARATHNA, H., HORRILLO-CARABALLO, J., SPIVACK, M. & REEVE, D.E.: "On modelling cross-shore beach morphology", *Journal of Coastal Research*, *issue. 64*, pp. 671-675, 2011
Beach evolution models are normally applied in a prognostic fashion, with parameters and boundary conditions estimated from previous experience or other forecasts. Here, we develop a beach profile evolution model based on a diffusion formulation that uses historic observations of beach profiles to solve the model governing equation in an inverse manner to determine some key model parameters. Then we solve the model equation to predict future beach profiles. The historic data used to demonstrate the beach profile evolution model are from the Milford-on-Sea beach at the Christchurch Bay, United Kingdom. The paper describes the methodology used for recovering key model parameters, diffusion coefficient and a time- and space-varying diffusion coefficent from the measured cross-shore profile data and then demonstrate the application of the model to predict future crossshore beach profiles. Despite its simplicity, the predictions of cross-shore beach profiles are in good agreement with measured data.

138. KARUNARATHNA, H., HORRILLO-CARABALLO, J.M., RANASINGHE, R., SHORT, A.D. & REEVE, D.E.: "An analysis of the cross-shore beach evolution of a sandy and a composite gravel beach", *Marine Geology*, *vol. 299-302*, pp. 33-42, DOI: 10.1016/j.margeo.2011.12.011, 2012
In this paper, beach profile surveys acquired over more than a decade at a sandy beach (Narrabeen Beach, New South Wales, Australia) and a composite sand–gravel beach (Milford-on-Sea, Christchurch Bay, UK) are analysed to compare and contrast cross-shore morphodynamics of the two beach types. The different behavioural characteristics of the two beach types at decadal, inter-annual and intra-annual time scales are investigated. Comparisons of beach profiles with Dean's equilibrium profile and Vellinga's erosion profile show that the Dean's profile satisfactorily represents the time mean profiles of both beach types. Statistical and Empirical Orthogonal Function (EOF) analyses confirm the generally accepted model that the inter-tidal zone is the most morphodynamically active region on a sandy beach whereas the swash zone is the most dynamic region on a mixed sand–gravel beach. The results also imply that during storms composite sand–gravel beaches may become unstable due to cutback of the upper beach while sandy beaches are more likely to be unstable as a result of beach lowering due to sediment transport from the inter-tidal zone to the sub-tidal zone during storms. EOF results also show that Milford-on-Sea beach is in a state of steady recession while the Narrabeen Beach shows a cyclic erosion–accretion variability. A multivariate technique (Canonical Correlation Analysis, CCA) shows that on the composite beach a strong correlation exists between incident wave steepness and profile response, which could be attributed to the unsaturated surf zone, whereas on the sandy beach any correlation is much less evident.

139. KARUNARATHNA, H., HORRILLO-CARABALLO, J.M., SPIVACK, M. & REEVE, D.E.: "Analysis of key parameters in a diffusion type beach profile evolution model", *Continental Shelf Research*, *issue. 31*, pp. 98-107, DOI: 10.1016/j.csr.2010.11.008, 2011
Diffusion type formulations are commonly used in beach profile evolution models. The practical idea behind that is to map the behaviour of the beach profile onto a simple mathematical model that exhibits the same behaviour under defined operating conditions. The success of this approach is based on the accurate determination of key parameters in the diffusion model that govern its behaviour, using observed beach behaviour in the field. In order to determine these parameters, i.e. diffusion coefficient and a time and space varying source function, we used observations of historic beach profiles at Milford-on-Sea beach in Christchurch Bay, Dorset, United Kingdom. The relationship between the diffusion coefficient and Dean's equilibrium profile was investigated, leading to a new interpretation of the diffusion coefficient in terms of the sediment characteristics. The analysis also shows the significance of the diffusion process in the medium to long term evolution of the beach profile. A canonical correlation analysis (CCA) was undertaken in order to identify patterns of behaviour between wave conditions and source terms, and the possible correlations between them. The analysis provides strong evidence of a useful link between the source term in the simple dynamical equation and the distribution of wave steepness.

140. KRAMER, S.C., FUNKE, S.F. & PIGGOTT, M.D.: "A continuous approach for the optimisation of tidal turbine farms.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
The optimal placement of individual devices within a tidal turbine farm is a challenging problem that may benefit

greatly from automated optimisation methods. A previously published gradient-based approach for the optimal placement/arrangement of turbines significantly reduces the number of required iterations over traditional optimisation methods. This allows for a higher level of computational cost, and hence realism, in the hydrodynamic model used in every optimisation iteration. Here, we introduce a closely related approach that optimises for a turbine density field (referred to here as the “continuous” approach) instead of the positions of individual turbines (the “discrete” approach). Its advantages are: (1) it requires less mesh resolution than the discrete approach and hence has lower computational costs; (2) the number of turbines does not need to be chosen in advance – this allows for the inclusion of perturbine-costs to be included in the optimisation, and as a byproduct returns an estimate for the optimal number of turbines on a site; (3) it allows for the inclusion of more complex site design constraints. We present a number of cases to demonstrate the validity of the method. The optimal number of turbines predicted by the continuous approach is shown to agree well with the results of running several discrete optimisations with different numbers of turbines, giving confidence to the validity of the new approach. In a realistic case we show how non-convex domain sites can be optimised. Furthermore, this approach naturally supports complex constraints such as maximum bathymetry gradients above which turbines cannot be installed, and the simultaneous optimisation of multiple, potentially interacting farms.

141. KREGTING, L., BLIGHT, A., ELSÄßER, B. & SAVIDGE, G.: "The influence of water motion on the growth rate of the kelp Laminariahyperborea", *Journal of Experimental Marine Biology and Ecology*, *vol. 448*, pp. 337-345, DOI: 10.1016/j.jembe.2013.07.017, Oct-13
The kelp Laminaria hyperborea is a dominant component of the subtidal nearshore ecosystem and is subjected to a heterogeneous wave and current climate. Water motion is known to influence physiological processes in macroalgae such as photosynthesis and nutrient uptake attributed to mass-transfer limitation. The study attempts to establish the effect of water motion on the growth rates of blades and elongation rates of the stipes of L. hyperborea at adjacent wave-exposed and wave-sheltered locations over a 12 month period from field observations. The observations were supported by detailed physical and chemical measurements (light, temperature, seawater nutrient concentrations and hydrodynamics) and of tissue carbon and nitrogen concentrations together with δ13 carbon. Despite a 30% difference in the root mean square of the velocity (Velrms) between the two survey locations, there was no evidence to suggest that water motion had any direct influence on the growth rates of either the blades or elongation of stipes of L. hyperborea. No significant differences were observed between either environmental or plant physiological variables between the sheltered and exposed locations. Using an integral velocity parameter (Velrms) the present study also highlighted the importance of the tidally induced current component of water flow in the subtidal zone.

142. LAKE, T., MASTERS, I. & CROFT, T.N.,: "Review of Individual Based Modelling Techniques in a Marine Environment", *Proc. 5th Conference on Computational Methods in Marine Engineering (ECCOMAS Marine 2013), Hamburg*, 2013
Individual based modelling techniques offer an opportunity to explore the effects of animal behaviour on the environment, and the effects of changes in the environment on animal behaviour. This holds particular relevance in the growing fields of wave and tidal power, where developers are often required to investigate the potential effect of their devices. A number of approaches to IBMs are discussed, including some of the additional challenges faced applying these methods to the marine environment.

143. LEWIS, M.J. & NEILL, S.P.: "The importance of waves within assessing the impact of tidal energy schemes", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Environmental impacts of proposed marine renewable schemes need to be understood. Typically, tide-only hydrodynamic models are employed to investigate the effect of proposed tidal energy converter arrays to sediment transport processes; however, storm waves are a very important process in the control and movement of these sandbanks. Twelve years of bathymetric data (1991-2002) from annual surveys of the Nash and Helwick sand banks in the Bristol Channel (UK) have been analysed. The inter-annual variability within storm wave events capable of erosion were calculated, and compared to the change in bathymetry at both sand banks. Such analysis indicated that the natural variability within storm wave events could be responsible for the observed inter-annual variability of sand bank volume and morphology. Therefore, surface waves should be included within a hydrodynamic model when determining the sediment transport impact of marine renewable schemes. Furthermore, the natural variability within a sandbank system needs be understood before the impact of a marine renewable scheme is determined.

144. LEWIS, M.J. & NEILL, S.P.: "The importance of inter-annual variability in assessing the environmental impact of tidal energy schemes", *2nd Oxford Tidal Energy Workshop (OTE 2013), Department of Engineering Science, Oxford University*, pp. 49-50, 18-19 March 2013
The environmental impacts of proposed marine renewable schemes need to be understood within the context of natural variability. The inter-annual variability of Helwick Bank (in the Bristol Channel, U.K.) was investigated (1995

– 2002) and correlated to the variability within the simulated wave climate of the same period; therefore, the influence of (and natural variability within) the wave climate may need to be included when determining the likely impact of tidal turbine schemes to offshore sand banks, systems which protect our coastlines from the impact of storm waves. Indeed, more complex modelling techniques may be required to determine the environmental impact, rather than a 2-dimensional tide only hydrodynamic model.

145. LEWIS, M.J., HASHEMI, M.R., NEILL, S.P. & ROBINS, P.E.: "The direct effect of waves on the tidal stream energy resource", *1st International Conference on Renewable Energies Offshore, Lisbon, Portugal*, DOI: 10.1201/b18973-25, 24-26 November 2014
The wave climate at a number of potential UK tidal stream energy sites was analysed using a 7 year SWAN wave model simulation and compared to the M2 tidal ellipse (major semi-diurnal lunar component) calculated from a ROMS tidal model. A significant proportion was found to be at an angle oblique (> 20°) to the axis of rectilinear tidal flow (> 50% of the time between 2005 and 2011). The influence of surface waves upon tidal velocities was studied using a dynamically coupled 3D hydrodynamic ROMS-SWAN model (COAWST) for an idealized headland tidal stream energy site. The presence of waves reduced the net tidal stream energy re-source over a tidal cycle (Δ P) by 10% per 1m increase in wave height (R2 94%). Our research indicates that it is essential to consider the wave climate within tidal stream energy resource assessments and within studies of device interaction with the resource.

146. LEWIS, M.J., NEILL, S.P. & HASHEMI, M.R.: "Waves, wave direction and the tidal stream energy resource", *TOS/ASLO/AGU Ocean Sciences meeting, Honolulu, Hawaii*, 23-28 Feb 2014
A wide range of factors must be considered when selecting sites that will be suitable for tidal stream energy arrays. Further, the force of waves acting upon a tidal turbine will need to be considered by designers and engineers. Much research has been focused on the influence of surface waves upon tidal turbine performance, such as fatigue loading and array optimisation, via flume experiments and numerical models. Studies of the interaction between a tidal turbine and realistic oceanographic conditions typically assume waves to be 'inline' to the tidal flow (waves either propagating with, or against, the tidal current); however, wave direction is affected by a number of processes, such as refraction and wave-current interaction. Therefore, wave direction may be out-of-line (angular) to the tidal flow for extended periods of time at a particular site, which may affect the tidal turbine design required and the amount of time electricity production can occur. The wave climate of the northwest European shelf was simulated over the 7 years (2005 – 2011) with a 1/24° resolution SWAN model, and the tidal currents around the UK were simulated for 30 days with a 3-dimensional (1/24° horizontal resolution) ROMS hydrodynamic model. The direction of the wave climate at 3 potential UK tidal energy sites was compared to the simulated major axis angle of semi-diurnal lunar (M2) tidal flow. A significant wave climate out-of-line to the tidal flow was found at all three sites. Angular wave events occurred between 67% (site A), 88% (site B), and 90% (site C) of the 7-year wave simulation, with extreme wave events above 10m (wave height) and 10s (wave period) being simulated at an angle oblique to the tidal flow. Therefore, the tidal turbine industry must consider wave direction in design and resource assessment. Dynamically coupled SWAN-ROMS COAWST model simulations of an idealised headland tidal energy site (40m water depth, 2m/s tidal current) was used to study the direct effect of waves upon the tidal stream energy resource. Although wave-induced modification of tidal velocity profiles was found to be small, a large effect to the tidal stream power available (over the course of a tidal cycle) was found because tidal power is a function of the cube of the tidal velocity. Therefore, much more research is required to understand realistic oceanographic conditions at tidal stream energy sites.

147. LEWIS, M.J., NEILL, S.P. & HASHEMI, M.R.: "Realistic wave conditions and their influence on quantifying the tidal stream energy resource", *Applied Energy*, *vol. 136*, pp. 495-508, DOI: 10.1016/j.apenergy.2014.09.061, 2014
When selecting suitable sites for tidal stream energy arrays a wide range of factors must be considered, from the magnitude of the tidal stream resource, to realistic oceanographic conditions. Previous computational and laboratory-scale investigations into the impact of waves upon tidal turbines (such as turbine blade loadings) and turbine arrays (such as array configuration) typically assume that waves propagate "inline" to the tidal current (waves following or waves opposing the tidal current with a 20° tolerance limit). We investigated the wave climate at typical tidal stream energy sites across the British Isles. The wave climate was simulated at 18 sites using a 7-year (2005–2011) SWAN wave model simulation of the northwest European shelf seas. The principal semi-diurnal lunar constituent (M2) was also estimated at these sites using the three-dimensional ROMS tidal model. A significant proportion of the wave climate (between 49% and 93% of the time), including extreme wave events (>10 m wave heights), was found to be propagating in a direction which was "oblique" to the major axis of tidal flow (i.e. waves which propagate at an angle to the tidal current with a 20° tolerance limit) at all 18 selected sites. Furthermore, the average "inline" wave climate was 2.25 m less in height and 2 s less in wave period in comparison to the oblique wave climate. To understand the direct effect of waves upon the tidal stream resource,

the dynamically wave-tide coupled COAWST modelling system was applied to an idealized headland case study, which represented the typical tide and wave conditions expected at first generation tidal stream energy sites. Waves were found to alter the simulated tidal velocity profile, which, because tidal stream power is proportional to velocity cubed, reduced the theoretical resource by 10% for every metre increase in wave height (R2 94% with 22 degrees of freedom) – depending upon wave period and direction. Our research indicates that wave angle should be considered when quantifying the impact of waves upon tidal turbines, such as computational fluid dynamic (CFD) studies, or laboratory-scale experiments of wake characteristics and turbine fatigue loading. Further, dynamically coupled tide-wave models may be necessary for a thorough resource assessment, since the complex wave-tide interaction affected the tidal resource; however, in situ observations of tidal velocity profiles during a range of wave events will be essential in validating such modelling approaches in the future.

148. LONGSHAW, S.M., ROGERS, B.D. & STANSBY, P.K.: "Integration Of Spring Physics With The SPH Method For Quasi-Solid To Fluid Interaction Using GPU programming", *8th SPHERIC workshop, Trondheim, Norway*, 6-4 June 2013
Turbines used in an unpredictable natural environment can potentially suffer from the impact of surrounding objects or animals. When turbines are placed underwater this problem primarily comes from large flotsam and substantial marine life. In order to consider the implications of this problem on the design of such turbines it is necessary to be able to simulate numerically a quasi-rigid body and its interaction with rigid boundaries whilst it is suspended in fluid. Smoothed Particle Hydrodynamics (SPH) appears well suited to solving this problem, however methods aimed at simulating elastic bodies and those aimed at simulating fluid flows are typically disparate. Combination of the methods therefore requires a methodology to couple them by way of an interface. Alternatively the SPH methods suited to fluid flow simulation could be combined with a particle based method such as a Mass-Spring-Damper (MSD) model to enforce Hookean restrictions on certain particles within an SPH simulation. It is this second possibility which is presented here, where it is shown that the MSD technique neatly combines with a weakly compressible GPGPU (General Purpose Graphics processing Unit) based implementation of the SPH method. Consideration towards the engineering realism of the elastic body represented by the MSD method is given, with a technique to correct a global spring constant and damping coefficient on a per particle basis presented. Simple extension test cases of a two-dimensional elastic square are provided to highlight the effectiveness of the correction method. Results show good correlation to the expected ideal and questions as to the best method to select a global spring constant are also posed and discussed. An illustrative example of the MSD model inter-operating with the SPH method is also provided.

149. MACIVER, R., CHRISTIE, C. & GLEIZON, P.: "Wave-Current Interaction in the Pentland Firth and Orkney Waters: Wave Field Effects", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
The influence of tidal currents on the wave conditions at proposed wave and tidal energy project locations in the Pentland Firth and Orkney Waters region off the north-west coast of Scotland is investigated with a coupled two-dimensional (horizontal) hydrodynamic and wave model. Simulated wave conditions are compared with field observations at two sites within the region: the European Marine Energy Centre's (EMEC's) wave test site at Billia Croo and a deployment at the western end of the Pentland Firth undertaken by the Environmental Research Institute (ERI). Observed modulations in the integrated wave parameters are associated with the temporal and spatial variation in the tidal streams of the region.

150. MACIVER, R., REDDY, N. & VENUGOPAL, V.: "Representing wave energy extraction in regional scale numerical models.", *TeraWatt Position Papers*, pp. 49-73, *ISBN: 978-0-9934256-0-8*, 2015
Commercial wave energy projects are certain to require the development of 'farms' or 'arrays' consis ng of mul ple wave energy converters. It will be necessary to demonstrate the effects of an individual array, and the cumula ve effects of mul ple arrays, on the physical and ecological processes of the region hos ng the arrays as part of the environmental impact assessment (EIA). The aim of this document is to present the state of the art in numerical modelling techniques capable of achieving this and to suggest approaches for modelling wave energy extrac on for the purpose of s mula ng a discussion with device and project developers concerning the most appropriate method. Spectral wave models and Boussinesq/Mild-slope models are considered the most appropriate for regional scale effects. The advantage of spectral wave models is their computa onal efficiency which permits the study of large domains and the poten al to couple with hydrodynamic and coastal process models. Accurate representa on of wave energy devices will require a parametric descrip on of the wave/structure interac on in terms of a frequency and direc onally dependent func on for the transmission and reflec on coefficient. These coefficients will depend on the device's absorp on characteris c and geometry. At present transmission coefficients are inferred from func onal rela ons such as a rela ve capture width (non-dimensional ra o of absorbed hydrodynamic power typically expressed as a func on of frequency) or a power matrix (absorbed hydrodynamic power as a func on of frequency and incident wave height). It is recognised that this is commercially sensi ve

informa on. However, through discussion with developers it is intended to establish representa ve func ons for the principle classes of wave energy device that may be used to study the effect of generic wave energy devices.

151. MAGAR, V., LEFRANC, M., HOYLE, R.B. & REEVE, D.E.: "Spectral quantification of nonlinear behaviour of the nearshore seabed and correlations with potential forcings at Duck, N.C., USA", *arXiv*, pp. 50, 2011
Local bathymetric, quasi-periodic patterns of oscillation are identified from 26 years of monthly profile surveys taken at two shore-perpendicular transects at Duck, North Carolina, USA. The data cover both the swash and surf zones. Singular Spectrum Analysis (SSA) and Multi-channel Singular Spectrum analysis (MSSA) methods are applied, on the shoreface, to three potential forcings: the monthly wave heights, the monthly mean water levels and the large scale atmospheric index known as the North Atlantic Oscillation. The patterns within these forcings are compared to the local bathymetric patterns; it is found that the patterns extracted using SSA and MSSA agree well with previous patterns identified using wavelets and confirm the highly non-stationary behaviour of beach levels at Duck. This is followed by analysis of potential correlations between the local bathymetry (at the two transects) and hydrodynamic and atmospheric patterns. The study is then extended to all measured bathymetric profiles, covering an area of 1100 m (alongshore) by 440 m (cross-shore). MSSA showed no collective inter-annual patterns of oscillations present in the bathymetry and the three potential forcings. Annual and semi-annual cycles within the bathymetry are found to be strongly correlated with the monthly wave height, in agreement with the SSA findings. Other collective intra-annual cycles besides the semi-annual were identified; they were all correlated with the North Atlantic Oscillation.

152. MARTIN-SHORT, R., KRAMER, S.C., HILL, J., AVDIS, A. & PIGGOTT, M.D.: "Tidal resource extraction in the Inner Sound of Stroma, UK: potential impacts on flow regime and sediment transport", *Renewable Energy*, *vol. 76*, pp. 596-607, DOI: 10.1016/j.renene.2014.11.079, Apr-15
Large-scale extraction of power from tidal streams within the Pentland Firth is expected to be underway in the near future. The Inner Sound of Stroma in particular has attracted significant commercial interest. To understand potential environmental impacts of the installation of a tidal turbine array a case study based upon the Inner Sound is considered. A numerical computational fluid dynamics model, Fluidity, is used to conduct a series of depth-averaged simulations to investigate velocity and bed shear stress changes due to the presence of idealised tidal turbine arrays. The number of turbines is increased from zero to 400. It is found that arrays in excess of 85 turbines have the potential to affect bed shear stress distributions in such a way that the most favourable sites for sediment accumulation migrate from the edges of the Inner Sound towards its centre. Deposits of fine gravel and coarse sand are indicated to occur within arrays of greater than 240 turbines with removal of existing deposits in the shallower channel margins also possible. The effects of the turbine array may be seen several kilometres from the site which has implications not only on sediment accumulation, but also on the benthic fauna.

153. MASTERS, I., WILLIAMS, A., CROFT, T.N., TOGNERI, M., EDMUNDS, M., ZANGIABADI, E., FAIRLEY, I. & KARUNARATHNA, H.: "A Comparison of Numerical Modelling Techniques for Tidal Stream Turbine Analysis", *Energies*, *vol. 8*, pp. 7833-7853, DOI: 10.3390/en8087833, 2015
To fully understand the performance of tidal stream turbines for the development of ocean renewable energy, a range of computational models is required. We review and compare results from several models of horizontal axis turbines at different spatial scales. Models under review include blade element momentum theory (BEMT), blade element actuator disk, Reynolds averaged Navier Stokes (RANS) CFD (BEM-CFD), blade-resolved moving reference frame and coastal models based on the shallow water equations. To evaluate the BEMT, a comparison is made to experiments with three different rotors. We demonstrate that, apart from the near-field wake, there are similarities in the results between the BEM-CFD approach and a coastal area model using a simplified turbine fence at a headland case.

154. MCCAIG, C., SABATINO, A., & HEATH, M.R.: "Statistical modelling of suspended sediment off Stonehaven", *MASTS Annual Science Meeting, Heriot-Watt University, Edinburgh, United Kingdom*, 27-29 August 2013
Changes in suspended sediment concentration (SSC) are important for both the physical and ecological environment. One of the main impacts is on the attenuation of light intensity with depth, which affects phytoplankton and macrophyte primary production, and the environment for visual predators. However, detailed data on SSC are relatively scarce, so both dynamic and statistical models which may predict SSC from more readily available data are potentially valuable. We analysed a dataset of >400 turbidity profiles collected at weekly intervals during 2007-2011 at the Marine Scotland Science sampling site off Stonehaven on the east of Scotland. We sought to establish a statistical General Additive Model (GAM) of SSC at a given altitude above the seabed with explanatory variables being seabed depth, tidal, wind, wave, and river outflow data. Alternative models were assessed with Akaike's Information Criterion to choose between the fits offered by different models. Our final model provided a highly significant fit to the observed data from the main sampling site. We then tested the model

by applying it to independent data collected at secondary sampling sites in both shallower and deeper water in the vicinity and showed that the model provided as significant account of the SSC dynamics at these site also.

155. MCNATT, C., VENUGOPAL, V., FOREHAND, D. & PAYNE, G.: "Experimental Analysis of WEC Wave Fields", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
In a previous theoretical paper submitted to EWTEC, the authors showed that the wave energy converter (WEC) wave field can be accurately and analytically represented by cylindrical linear waves with the appropriate coefficients. In that paper, the coefficients were found computationally using the boundary-element method software, WAMIT. For the present paper, experiments were conducted in the newly refurbished University of Edinburgh Curved Wave Tank to determine the same cylindrical coefficients for progressive waves. The experiments employed two body geometries, an attenuator consisting of a horizontal pitching cylinder, and a terminator made up of a bottom-hinged flap. An array of 59 wave gauges was arranged in a circle-spoke pattern, where the circle of wave gauges was necessary for deriving the cylindrical coefficients, and the spokes, which extended radially further afield, were used for validation. Both the scattered and the radiated waves of the bodies were examined at three frequencies. High-order harmonics were present in a number of the wave fields, and tank reflections were problematic. Despite this, the linear analytical wave field, whose coefficients were found experimentally, agrees well with the experimentally measured linear wave field at points other than those used to derive the coefficients. The results serve to validate linear wave theory as it relates to the wave field and reinforce the concept that these waves can be used to compute WEC performance and wave farm interactions and impacts.

156. NEILL, S.P.: "Impact of tidal stream arrays on sediment dynamics", *International Symposium on Climate change and human activities: Coastal Consequences and Responses. Shanghai, China*, 28-31 Oct 2012
To reduce greenhouse gas emissions and aid sustainable development, there is an urgent need to support our electricity generating capacity through the development of low carbon technologies, particularly those generated from renewable sources. The ocean is a vast and largely untapped energy resource, and many countries around the world are developing tidal stream turbine projects, with an aim to generate electricity at array scale within the next 5-10 years. Large scale exploitation of the tidal stream resource is likely to alter 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 residual tidal currents could translate into large changes in the sediment dynamics. Here, I investigate this effect in relation to the flow past headlands, some of the most attractive regions for exploitation of the tidal stream resource. However, tidal flow past headlands generates headland eddies, with an opposite sense of vorticity between the flood and ebb phases of the tide. Net bedload convergence within these eddy systems leads to the formation and maintenance of headland sandbanks, features which have horizontal length scales of up to 10 km, and so are important in terms of coastal flood protection due to their role in wave refraction and breaking. Therefore, any tidal energy scheme which could lead to changes in the morphodynamics of these headland sandbanks could have implications for coastal flooding. This impact is demonstrated here initially by a series of idealised 3D numerical model experiments, and then applied to a real case study in the English Channel, UK.

157. NEILL, S.P. & IGLESIAS, G.: "Impact of WEC array operation on nearshore processes", *Fourth International Conference on Ocean Energy (ICOE), Dublin, Ireland*, 17-19 Oct 2012
Before wave energy converter (WEC) arrays can be used to generate electricity at large scale, their environmental impacts need to be understood. Here, we examine the impact of large-scale WEC array operation on sand bars. Sand bars have an important role in natural coastal processes, since they protect our coastlines from the impact of storm waves. Since the wave climate between a WEC array and the coast will likely be modified by largescale energy extraction, this could disrupt the natural process which maintains sand bars, affecting the location of wave breaking. We examine this hypothesised impact through application of a 1D cross-shore wave and sediment transport model. The model is applied initially to simulate natural sand bar formation. Wave energy is subsequently extracted at the model boundary, representing WEC array operation, and the morphodynamic impact assessed. Our results demonstrate that, under certain conditions, WEC array operation can lead to enhanced sand bar formation. Since reduced water depth over the bar enhances depth-induced wave breaking, WEC array operation could provide enhanced coastal protection from storm waves.

158. O'HAGAN, A.M., HUERTAS, C., O'CALLAGHAN, J. & GREAVES, D.: "Wave energy in Europe: views on experiences and progress to date", *Journal of Marine Energy*, *vol. 14*, pp. 180–197, DOI: 10.1016/j.ijome.2015.09.001, Jun-16
Through the Intelligent Energy Europe-funded SOWFIA project, the experiences of developers, regulators and stakeholders in relation to consenting wave energy deployments to date was assessed and analysed. The work focussed on wave energy test centres in Europe and involved consultation with wave energy device and project developers, regulatory authorities, stakeholders, environmental consultants and others through dedicated workshops and questionnaire surveys. Themes that arise in the analysis relate to planning and consenting

processes, administrative procedures, Environmental Impact Assessment and stakeholder consultation. An analysis of the barriers as perceived by those consulted is presented and discussed, and recommendations are drawn from the analysis within each of the themes. In particular the need for Maritime Spatial Planning (MSP) to alleviate complex planning and consenting processes; the need for coordination of administrative procedures; the need for clearer requirements in the EIA process; and the need for early participation of stakeholders in consultation are discussed. Progress has been made in many EU ountries but certain priority areas remain to be addressed if wave energy is to realise its full potential.

159. OLCZAK, A., STALLARD,T. & STANSBY, P.K: "The Influence of Waves on Tidal Stream Turbine Wake Recovery", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
To predict the energy yield from multiple turbines at close proximity, it is necessary to understand the structure and extent of the region of reduced velocity, the wake, that develops downstream of each turbine. Both large-scale turbulence and surface waves are known to occur at tidal stream sites so it is important to understand the influence of these processes on turbine wake recovery. An experimental study is presented of the influence of surface waves on both the ambient flow and wake recovery of a single horizontal axis tidal stream turbine. A wake is generated using a rotor of diameter D = 0.27m, which develops mean thrust coefficient and tip speed ratio of 0.9 and 5.5 respectively. Mean velocity is 0.46 m/s and turbulence characteristics are similar to full-scale.Waves of depth parameter (kd) 1 to 3.13 are considered representing full-scale waves of 10-16 s over flow of 3.7 m/s in 31 m depth (approx.). Wake profiles immediately downstream of the rotor (2-4D) differ considerably with wave depth parameter. Far wake recovery is analysed for two wave conditions with comparable wave energy flux. Intermediate waves lead to reduced deficit at and below the centreline up to 12D downstream. Deep waves reduce deficit in the upper half of wake only for part of the wake extent. The relationship between wake structure and flow characteristics is discussed.

160. O'HARA MURRAY, R.: "Data acquisition and processing for TeraWatt", *TeraWatt Position Papers*, pp. 9-29, *ISBN: 978-0-9934256-0-8*, 2015
This report is the first of a series of position papers produced by the Engineering and Physical Science Research Council funded TeraWatt project. One aim of the TeraWatt project was the development of numerical regional scale wave and tidal hydrodynamic models for the assessment of the consequences of wave and tidal energy extraction on the physical and ecological environment. The project focused on the Pentland Firth and Orkney Waters (PFOW), although the Scottish east coast was also modelled as part of a sediment transport study. The main purpose of the models was to simulate the hydrodynamics for both baseline cases and cases with tidal and/or wave energy extraction, enabling an assessment of the changes to be made. Regional scale hydrodynamic models require a number of different datum types for preprocessing, e.g. preparing the model bathymetry, and post-processing, e.g. validating the model output with observational data.

161. O'HARA MURRAY, R.: "Tidal stream and wave energy array scenarios for the Pentland Firth and Orkney Waters Strategic Area", *TeraWatt Position Papers*, pp. 31-47, *ISBN: 978-0-9934256-0-8*, 2015
The Orkney Islands and surrounding waters contain a significant portion of Scotland's tidal and wave energy resource. For this reason, a number of tidal and wave energy sites have been granted agreement for lease by The Crown Estate (TCE) as areas for commercial renewable energy development within the region known as the Pentland Firth and Orkney Waters Strategic Area (PFOW). The development sites granted agreements for lease by TCE in 2010 formed the PFOW Round One Development Sites (BVG Associates, 2011; The Crown Estate, 2013) and it is these sites that are being considered in this study. At the time of writing the number of development sites within the PFOW has just been revised; with one more 30 MW site being leased to Scotrenewables Tidal Power Ltd and the number of wave sites being reduce to two, totalling 250 MW, (Marine Scotland, 2015). This revision reflects the rate at which tidal and wave technology has developed in recent years and the current economic climate. The TeraWatt project decided to use the original PFOW Round One Development Sites on the grounds that this was originally considered to be viable by the Scottish Government and TCE. The wider TeraWatt study aims to model tidal and wave processes in the PFOW using three dimensional hydrodynamic and spectral wave numerical models, and to include the extraction of tidal and wave energy in the models. Such models will greatly enhance our understanding of the impact that removing tidal and wave energy may have on physical and ecological processes within the region.

162. O'HARA MURRAY, R.: "Data acquisition and the development of realistic tidal and wave energy scenarios for numerical modelling of Orkney Islands waters, Scotland", *Terawatt special issue of the Journal of Ocean and Coastal Management*, 2015
The Orkney Islands and surrounding waters (the region known as the Pentland Firth and Orkney Waters Strategic Area, PFOW) contain a significant portion of Scotland's tidal and wave energy resource. In the context of a wider study to model tidal and wave processes, and planned renewable energy extraction, in PFOW using 3D hydrodynamic and spectral wave numerical models, we define the data used for the development of these

hydrodynamic models. Such data, i.e. high resolution bathymetry, model boundary conditions and measurements for model validation, are hard to obtain in extreme environments such as PFOW. This paper examines the characteristics, and selection criteria, of the data used for the development of the models. Most of these data are freely available, and could form part of an open source marine renewable energy hydrodynamic modelling methods toolbox. In order to include the planned tidal and wave energy developments in the hydrodynamic models of the wider study, realistic tidal and wave device array scenarios are required. However, there is still considerable uncertainty regarding the type of devices that will be deployed and device array layouts. Here, we describe the process undertaken to develop a small number of generic device types and array scenarios for the PFOW, based on insight provided by documentation submitted by developers as part of the Scottish marine licensing process, in consultation with industry. For tidal developments, an algorithm was developed to determine the site specific array configuration, taking into account the number of turbines, water depth, tidal current direction and the spatial distribution of mean tidal speed. The wave development sites did not require such detailed site specific placement of devices, and the generic layouts could simply be constructed in most cases without the need for detailed site specific resource characterisation. It is anticipated that the renewable energy industry will be able to adopt our data selection criteria to ensure models developed for environmental impact assessments follow best practice in order to satisfy the quality requirements of the regulator. Similarly, the methodologies developed for characterising generic device types and array layouts will be useful to academia and government researchers, who do not necessarily have access to detailed device and site specific information.

163. O'HARA MURRAY, R., PRICE, D. & GALLEGO, A.: "A look to the future: maximizing the sustainable tidal stream energy potential of the Pentland Firth", *MASTS Annual Science Meeting, Glasgow, United Kingdom*, 30 Sep - 2 Oct 2015
It is estimated that Scotland's marine area contains 25% of Europe's tidal resource, and the Scottish Government has identified 10 broad areas of search for future tidal stream energy exploitation (The Scottish Government, 2015). One of these areas is the Pentland Firth and Orkney Waters Strategic Area (PFOW), as it contains the highest tidal stream energy resource in Scotland (Black & Veatch, 2005). To date six sites in and around the Pentland Firth have been leased by The Crown Estate to developers for commercial tidal stream energy development within the PFOW. Together, these sites have an aspirational energy generating capacity of approximately 1 GW. In order to harness more energy from the Pentland Firth, careful marine spatial planning will be required, since any single development has the potential to change the flow within the Pentland Firth region to an extent (Adcock et al., 2013; Draper et al. 2014; Vennell, 2015). This work explores the options available for future tidal stream energy extraction in the Pentland Firth region, beyond the 1 GW currently leased to developers, and aims to quantify some of the changes that may occur in the tidal stream. A 3D hydrodynamic model of the northern isles of Scotland has been developed using the Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2006). Potential tidal stream energy scenarios are represented within the model using a momentum sink, following the approach of Yang et al. (2013). A number of scenarios were explored based on recommendations from previous work (Adcock et al., 2013; Draper et al. 2014; Vennell, 2015). The results are used to construct a realistic future scenario representing the limit of tidal stream energy extraction in the region.This work is part of a wider study, the EPSRC-funded EcoWatt2050 project, aiming to model a realistic 2050 marine energy scenario, in order to better understand the potential, far field, environmental consequences of very large scale marine energy extraction in Scottish waters.

164. RAHMAN, A.A. & VENUGOPAL, V.: "Inter-Comparison of 3D Tidal Flow Models Applied To Orkney Islands and Pentland Firth for Resource Assessment.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
This paper presents the comparison of results from two open source 3D numerical models, namely Telemac3D and Delft3D, which are applied to the Pentland Firth and Orkney Waters in the United Kingdom. An extended description of the model setup is presented, with an elaboration on the physical and numerical parameters utilised in the models development. Both models are run using only the astronomical input and meteorological parameters are not considered. The models are then calibrated and validated using the IHO tidal gauges and Acoustic Doppler and Current Profiler (ADCP) measurements. Several values of bottom roughness and two different combinations of the water level and current as boundary inputs have been examined. The velocity components obtained from the numerical models are then compared at three water depths against the field data. The performance indices calculated between the model results and measured data illustrate that the model worked well. Also the results demonstrate that the values of bottom roughness and boundary condition inputs are critical in the prediction of current velocities.

165. REEVE, D.E., CHEN, Y., PAN, S., MAGAR, V., SIMMONDS, D.J. & ZACHARIOUDAKI, A.: "An investigation of the impacts of climate change on wave energy generation: The Wave Hub, Cornwall, UK", *Renewable Energy*, *vol. 36*, *issue. 9*, pp. P2404-2413, DOI: 10.1016/j.renene.2011.02.020, Sep-11
In this paper a generic methodology is presented that allows the impacts of climate change on wave energy

generation from a wave energy converter (WEC) to be quantified. The methodology is illustrated by application to the Wave Hub site off the coast of Cornwall, UK. Control and future wave climates were derived using wind fields output from a set of climate change experiments. Control wave conditions were generated from wind data between 1961 and 2000. Future wave conditions were generated using two IPCC wind scenarios from 2061 to 2100, corresponding to intermediate and low greenhouse gas emissions (IPCC scenarios A1B and B1 respectively). The quantitative comparison between future scenarios and the control condition shows that the available wave power will increase by 2–3% in the A1B scenario. In contrast, the available wave power in the B1 scenario will decrease by 1–3%, suggesting, somewhat paradoxically, that efforts to reduce greenhouse gas emissions may reduce the wave energy resource. Meanwhile, the WEC energy will yield decrease by 2–3% in both A1B and B1 scenarios, which is mainly due to the relatively low efficiency of energy extraction from steeper waves by the specific WEC considered. Although those changes are relatively small compared to the natural variability, they may have significance when considered over the lifetime of a wave energy farm. Analysis of downtime under low and high thresholds suggests that the distribution of wave heights at the Wave Hub will have a wider spread due to the impacts of climate change, resulting in longer periods of generation loss. Conversely, the estimation of future changes in joint wave height-period distribution provides indications on how the response and power matrices of WECs could be modified in order to maintain or improve energy extraction in the future.

166. ROBINS, P.E. & NEILL, S.P.: "The impact of tidal energy extraction on the morphodynamics of the Irish Sea", *Fourth International Conference on Ocean Energy (ICOE), Dublin, Ireland*, 17-19 Oct 2012
Exploitation of the tidal energy resource has been demonstrated to reduce flow speeds and affect the deposition of coarse sediment in the vicinity of Tidal Energy Converter (TEC) arrays, yet the far reaching hydrodynamic and morphological effects have yet to be determined. This impact could be significant in areas where sand banks form regions that exhibit asymmetries in terms of the sediment flux. Certain locations within the Irish Sea have strong tidal currents which are favourable extraction by means of TEC arrays. In this study, we apply an unstructured morphodynamic model to the Irish Sea, firstly to evaluate the hydrodynamic resource, and then to investigate energy extraction scenarios. The model has been adapted to include an additional bed friction source term to represent energy extraction due to TEC arrays, sited at velocity locations off North West Anglesey, Wales.

167. ROBINS, P.E., LEWIS, M.J. & NEILL, S.P.: "Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes", *Renewable Energy*, *vol. 72*, pp. P311-321, DOI: 10.1016/j.renene.2014.07.037, Dec-14
Tidal Energy Converter (TEC) arrays are expected to reduce tidal current speeds locally, thus impacting sediment processes, even when positioned above bedrock, as well as having potential impacts to nearby offshore sand banks. Furthermore, the tidal dissipation at potential TEC sites can produce high suspended sediment concentrations (turbidity maxima) which are important for biological productivity. Yet few impact assessments of potential TEC sites have looked closely at sediment dynamics beyond local scouring issues. It is therefore important to understand to what extent exploitation of the tidal energy resource will affect sedimentary processes, and the scale of this impact is here assessed in relation to natural variability. At one such site in the Irish Sea that is highly attractive for the deployment of TEC arrays, we collect measurements of sediment type and bathymetry, apply a high resolution unstructured morphodynamic model, and a spectral wave model in order to quantify natural variability due to tidal and wave conditions. We then simulate the impacts of tidal-stream energy extraction using the morphodynamic model. Our results suggest that the sedimentary impacts of ‘first generation’ TEC arrays (i.e. less than 50 MW), at this site, are within the bounds of natural variability and are, therefore, not considered detrimental to the local environment. Yet we highlight potential environmental issues and demonstrate how impact assessments at other sites could be investigated.

168. ROBINS, P.E., NEILL, S.P. & LEWIS, M.J.: "Impacts of tidal-stream energy converter (TEC) arrays in relation to the natural variability of sedimentary processes", *2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR), University of the Highland and Islands, Stornoway, United Kingdom*, 28 April - 2 May 2014
Tidal-stream Energy Converter (TEC) arrays are expected to reduce tidal current speeds locally, thus impacting sedimentary processes, even when devices are positioned above bedrock. Tidal dissipation can produce high suspended sediment concentrations (turbidity maxima) which are important for biological productivity. Also, devices will potentially impact morphological features further afield, e.g., offshore sand banks and beaches. Yet few impact assessment studies of potential TEC sites have looked closely at sediment dynamics beyond local scouring issues. It is therefore important to understand to what extent exploitation of the tidal energy resource will affect sedimentary processes, and the aim of this research is to assess the scale of this impact in relation to natural variability, caused by both tidal currents and wave-induced currents.

169. RODRIGUEZ, M. & SPINNEKEN, J.: "A study on the interactions of nonlinear surface waves with fixed semi-submerged bodies", *Proceedings of the twenty-third International Ocean and Polar Engineering Conference*, pp. 539-547, 2013

The present paper addresses the problem of nonlinear diffraction of surface waves by a fixed horizontal rectangular body in two dimensions. A fully-nonlinear multiple-flux potential flow model is implemented as a numerical wave tank to model the diffracted wave field and to evaluate the wave-induced loads. This technique relies on a boundary element formulation and retains the full nonlinearity of all boundary conditions. The nature of fully-nonlinear hydrodynamic simulations is such that they often represent the solution in a form that does not enable a full understanding and interpretation of the underlying physics. This paper will aim to explain the hydrodynamics underpinning the above diffraction problem by providing a direct comparison between the numerical results and an existing semi-analytical approach demonstrated that second-order horizontal and vertical forces may contribute significantly to the overall load on the structure. This observation is confirmed with the fully-nonlinear numerical method. In contrast to the semi-analytical solution, the numerical method may be applied to bodies of arbitrary geometry subjected to highly nonlinear waves; recommendation for the extension of the present work being made when appropriate.

170. SABATINO, A., CLEMENT, R., HEATH, M. & MCKEE, D.: "Use of ocean colour remote sensing to monitor surface suspended solids", *TeraWatt Position Papers*, pp. 129-140, *ISBN: 978-0-9934256-0-8*, 2015
The depth to which sunlight penetrates below the sea surface is one of the key factors determining the species composition and productivity of marine ecosystems. The effects range from the rate and fate of primary production, through the performance of visual predators such as fish, the potential for refuge from predators by migrating to depth, to the scope for seabed stabilisation by algal mats. Light penetration depends partly on spectral absorption by seawater and dissolved substances, but mainly on the scattering caused by suspended particulate material (SPM). Some of this SPM may be of biological origin, but in coastal waters the majority is mineral material originating ultimately from seabed disturbance and land erosion, the latter being deposited in the sea by rivers and aerial processes. SPM is maintained in the water column or deposited on the seabed depending on combinations of hydrodynamic processes including baroclinic (density-driven) or barotropic (mainly tidal and wind driven) currents, and wave action (Ward et al. 1984; Huettel et al. 1996). Since tidal and wave energy extraction must alter these hydrodynamic properties at some scales depending on the nature of the extraction process, we can expect some kind of impact on the concentration of the SPM. If these are large enough, we may have to consider the extent to which these may impact the underwater light environment and the local or regional ecology. Whilst several coupled hydrodynamic-sediment models exist to predict SPM distributions in aquatic systems, their skill level in open coastal and offshore marine waters is acknowledged to be relatively low. This is largely because the processes are not well understood and the formulations are largely based on empirical relationships rather than fundamental physical principles. The models are also highly demanding in terms of calibration data and computational resources. Hence their utility for predicting relatively subtle effects arising from changes in flow or wave environments due to energy extraction devices seems rather low. Here, we summarise the key mathematical functions describing the processes involved in sediment suspension, and propose a lightweight onedimensional (vertical) model which can be used to scope the effects of changes in flow and wave energy on SPM.

171. SARUWATARI, A., INGRAM, D.M. & CRADDEN, L.: "Wave–current interaction effects on marine energy converters", *Ocean Engineering*, *vol. 73*, pp. 106-118, DOI: 10.1016/j.oceaneng.2013.09.002, 2013
Many countries have significant interests in generating electricity using waves and tidal current technologies. In energetic areas, waves and tidal currents interact for modifying the energy resource and impacting on the design conditions. Changes to the wave climate depend on the strength of the current and the relative wave direction. SWAN simulations of the wave climate around the Orkney Islands, with and without currents, show that considerable changes in the wave climate occur near sites of interest to wave and tidal energy project developers. Using circular statistics the effect of the relative angle between the waves and the current can be investigated. Local effects can lead to 150–200% increases in wave height when the waves oppose the current. These dramatic changes lead to an increase in wave power of over 100 kWm-1. The complex nature of the tides in the channels also leads to large changes in wave power during the so-called slack water period. Wave amplification diagrams are proposed to provide a convenient summary of wave–current effects at a particular site and allow a statistical analysis to be made. When performing resource analysis and site selection work for marine energy projects, wave–current interaction must be considered.

172. SCHMITT, P., ELSÄßER, B., COFFIN, M., HOOD, J. & STARZMANN, R.: "Field testing a full-scale tidal turbine Part 3: Acoustic Characteristics.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Like any new technology, tidal power converters are being assessed for potential environmental impacts. Similar to wind power, where noise emissions have led to some regulations and limitations on consented installation sites, noise emissions of these new tidal devices attract considerable attention, especially due to the possible interaction with the marine fauna. However, the effect of turbine noise cannot be assessed as a stand-alone issue, but must be investigated in the context of the natural background noise in high flow environments. Noise measurements

are also believed to be a useful tool for monitoring the operating conditions and health of equipment. While underwater noise measurements are not trivial to perform, this non-intrusive mon- itoring method could prove to be very cost effective. This paper presents sound measurements performed on the SCHOTTEL Instream Turbine as part of the MaRINET testing campaign at the QUB tidal test site in Portaferry during the summer of 2014. This paper demonstrates a comparison of the turbine noise emissions with the normal background noise at the test site and presents possible applications as a monitoring system.

173. SEQUEIRA, C.L. & MILLER, R.J.: "Loss mechanisms in tidal stream", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
This paper explores the loss mechanisms critical to the operation of a tidal stream turbine. This is motivated by the fact that there is an upper limit to the amount of power that may be removed from a tidal stream by a turbine. To generate the maximum electricity possible, the designer may therefore aim to minimise the ratio of loss to useful power. Computational predictions were undertaken on a horizontal axis tidal turbine in a channel with a blockage ratio of 0.07. At design point, the total loss for this case was 69.2% of the useful power extracted, Pshaft. This may be broken down to different sources: rotor profile loss, structural loss, and wake mixing loss. Wake mixing loss is shown to dominate with a value of 58.1% Pshaft. The composition of the wake mixing loss is then investigated. It is shown that in addition to the 'idealised' radial variation of velocity through the wake there was also significant circumferential variation. This circumferential variation is responsible for approximately two thirds of total wake mixing loss, while the remaining one third is due to radial variations. This result implies that wake mixing loss could be reduced by designing turbines which produce wakes with lower circumferential non-uniformity.

174. SIDE, J., HARRIS, R., WOOLF, D., BELL, M. & BROOKS, A.: "Impacts of climate change on built structures (offshore).", *MCCIP Science Review 2013*, pp. 295-301, DOI: 10.14465/2013. arc31.295-301, 2013
It is clear that all industry sectors deploying, operating and maintaining offshore structures (and their insurers) are aware of the possible impacts of climate change. However, at the present time, particularly given the range of uncertainties inherent in future prediction and the range of variability apparent in historical data, it tends to be more of a watching brief rather than a call for specific actions, and changes in operational practices, to be adopted. For significant wave height and storminess it is possible that the coming decades may see increasing trends in mean and extreme values. These short term trends, are observable in historical datasets and in future may be a result of changing climate, but equally may be explained by the natural variability that is so apparent within the historical data. The safeguard to ensure the adequate protection of offshore structures is the awareness of the variability and the short term fluctuations (pseudo-trends) that can be found in time series data for these parameters. Protection for offshore structures is also provided by designs to meet extreme criteria (e.g. the 100 year wave in combination with associated wind and current criteria). In the absence of evidence to the contrary it would seem inappropriate at this time to insist on more stringent thresholds given the variability in data and uncertainty in predictions. Once they are operational, additional protection to offshore structures is afforded not only by remote condition monitoring systems but also by regular inspection and maintenance. In this regard any short term trends in the frequency and severity of storms and associated wave heights (whether the result of climate change or not) may have implications for the weather windows in which such marine operations can be safely conducted. This in turn may result in delays before any necessary remedial measures can be undertaken.

175. STAGONAS, D., BULDAKOV, E. & SIMONS, R.: "Extreme wave loads on a vertical slender cylinder with and without current", *International Ocean and Polar Engineering Conference, Hawaii, USA*, 21-26 June 2016
This paper presents results of wave flume experiments on the interaction of a vertical, slender surface piercing cylinder with extreme waves in the presence and absence of sheared currents. Following, the new-wave approach according to which a deterministic wave group represents an extreme wave in a random sea, we employ focused waves to model extreme events. Using recently introduced experimental methodologies we accurately generate steep non-linear focused waves propagating over the sheared, inline and opposing currents. One of the comparative advantages of this methodological approach is the creation of focusing wave groups with the same linearized target spectrum for all conditions investigated. The focused waves interact with a slender cylinder placed at the focus point and a phase-base separation method is used to isolate the linear, quadratic sub- and super-harmonics and high frequency third-order spectral components of the wave/wavecurrent induced loads. Preliminary results are presented for different target spectra and different current direction and velocity. It is shown that the current related effects on the wave-current induced loads are not only a function of the direction and the velocity of the current but also of the linearised spectrum of the focused wave. It is also shown that these effects not only refer to the linear components of the wave+current induced loads but they also extend over the higher order components. Finally, we compare wave groups with their amplitudes and phases focused at the focusing point to wave groups with their amplitudes focused near the wavemaker. The former is found to result inhigher high frequency loads.

176. STRATIGAKI, V., TROCH, P., STALLARD, T., KOFOED, J.P., BENOIT, M., MATTAROLLO, G., BABARIT, A., FOREHAND, D. & FOLLEY, M.: "Large Scale Experiments on Farms of Heaving Buoys to Investigate Wake Dimensions, Near-Field and Far-Field Effects", *International Conference on Coastal Engineering, Santander, Spain*, 1-6 July 2012
The shrinking reserves of fossil fuels in combination with the increasing energy demand have enhanced the interest in renewable energy sources, including wave energy. In order to extract a considerable amount of wave power, large numbers of Wave Energy Converters will have to be arranged in arrays or farms using a particular geometrical layout. The operational behaviour of a single device may have a positive or negative effect on the power absorption of the neighbouring WECs in the farm (near-field effects). Moreover, as a result of the interaction between the WECs within a farm, the overall power absorption and the wave climate in the lee of the WECs is modified, which may influence neighbouring farms, other users in the sea or even the coastline (far-field effects). Several numerical studies on large WEC arrays have already been performed, but large scale experimental studies on near-field and far-field wake effects of large WEC arrays are not available in literature. Within the HYDRALAB IV European programme, the research project WECwakes has been introduced to perform large scale experiments in the Shallow Water Wave Basin of DHI, in Denmark, on large arrays of point absorbers for different layout configurations and inter-WEC spacings. The aim is to validate and further develop the applied numerical methods, as well as to optimize the geometrical layout of WEC arrays for real applications.

177. SUN, L., ZANG, J., EATOCK TAYLOR, R. & TAYLOR, P.H.: "Effects of wave spreading on performance of a wave energy converter", *29th International Workshop on Waves and Floating Bodies IWWWFB 2014, Osaka, Japan*, 30 March - 2 April 2014
Ocean waves are irregular, nonlinear and directionally spread (short-crested). The irregularity of waves can be considered by superposing components at different frequencies. In many frequency-domain analyses, second-order contributions can be calculated to take account of the nonlinearity in wave-structure interactions. The directional spreading of the waves is usually described by introducing a directional spectrum. Several directional spectra have been suggested by researchers [1]. In short-crested waves, the wave energy propagates in different directions around principal wave directions, which will affect the performance of Wave Energy Converters (WEC). Especially, less energy may be harnessed for some directionally sensitive WEC. In present paper, we have examined the performance of an attenuator type WEC by calculating the relative rotations (pitch and yaw motions) between floating modules in uni-directional and multi-directional waves. The emphases have been put on operational sea states and only linear incoming waves have been considered. In the next section, the description of multi-directional waves in a numerical model will be introduced briefly. Then the motions of an attenuator type WEC and shear forces (in vertical and horizontal directions) acting on power take-off system (PTO) will be investigated. Different wave spreadings have been considered.

178. TOGNERI, M. & MASTERS, I.: "The influence of micrositing on marine turbulence", *ASRANet International Conference on Offshore Renewable Energy, Glasgow, United Kingdom*, 15-17 Sep 2014
We present turbulence results from two acoustic Doppler current profiler (ADCP) measurement campaigns carried out in Ramsey Sound at two locations within 50m of one another. The first measurements were taken in 2009 and the second in 2011. In this paper we characterise turbulence only through turbulent kinetic energy (TKE) density and integral length scales. We briefly describe the methods used to calculate these parameters. We find that a flood-ebb asymmetry is present in the data from both measurement campaigns, but although the flood tides are similar at both locations, the ebb tides are much more energetic in the 2011 data than the 2009 data. We suggest that this may be due to specific geographical features to the north of the channel, or possibly to seabed features. We investigate the correlation between length scales and TKE density, and find that it is highly site-specific: it should not be assumed that for a given measurement location that highly energetic turbulence is associated with larger flow structures or vice versa.

179. VANDAMME, J., ZOU, Q.P & REEVE, D.E.: "Modelling floating object entry and exit using Smooth Particle Hydrodynamics", *Journal of Waterway, Port, Coastal and Ocean Engineering*, *vol. 137*, *issue. 5*, DOI: 10.1061/(ASCE)WW.1943-5460.0000086, Sep-11
This paper investigates fluid and floating object interaction using a novel adaptation of the weakly compressible smoothed particle hydrodynamics (WCSPH) method by incorporating a floating object model. In particular, this paper examines the water impact, hydrodynamic forces, fluid motions, and movement of objects in the conventional case studies of object entry and exit from still water. A two-dimensional wedge drop analysis was examined, and the hydrodynamic forces show acceptable agreement with published experimental and numerical results. The movement of the object is well predicted. The velocity field of the fluid domain is also captured. Simulations for water entry and exit of a buoyant and neutral density cylinder compares well with previous experimental, numerical, and empirical studies in penetration, free surface comparisons, and object movement.

These results provide a good foundation to evaluate the accuracy and stability of WCSPH for modeling the interaction between free surface flow and free moving floating objects.

180. VENUGOPAL, V. & REDDY, N.: "Wave resource assessment for Scottish waters using a large scale North Atlantic spectral wave model.", *Journal of Renewable Energy*, *vol. 76*, pp. 503-525, DOI: 10.1016/j.renene.2014.11.056, 2015
This paper reports the methodology established in the application of a numerical wave model for hindcasting of wave conditions around the United Kingdom, in particular for Scottish waters, for the purpose of wave energy resource assessment at potential device development sites. The phase averaged MIKE 21 Spectral wave model has been adopted for this study and applied to the North Atlantic region bounded by latitudes 10° N-70° N and longitudes 10° E-75° W. Spatial and temporal wind speeds extracted from the European Centre for Medium Range Weather Forecast (ECMWF) have been utilised to drive the wave model. A rigorous calibration and validation of the model has been carried out by comparing model results with buoy measurements for different time periods and locations around Scotland. Significant wave height, peak wave period and peak wave direction obtained from the model correlated very well with measurements. Spatially varying statistical mean and maximum values of the significant wave height and wave power obtained based on a one-year wave hindcasting are in good agreement with the UK Marine Atlas values. The wave model can be used with high level of confidence for wave hindcasting and even forecasting of various wave parameters and wave power at any desired point locations or for regions. The wave model could also be employed for generating boundary conditions to small scale regional wave and tidal flow models.

181. VENUGOPAL, V., NEMALIDINNE, R. & VÖGLER, A.: "Impact of Temporal Variation of Wind Input on Wave Parameters Prediction Using Numerical Wave Model", *EWTEC conference, Nantes, France,*, 7-10 Sep 2015
This study analyses the impact of temporal variation of wind input on wave hindcasting of wave conditions using a numerical wave model. The third generation spectral wave model, MIKE21 suite, has been adopted for this study and applied to the North Atlantic region bounded by latitudes 10oN – 70oN and longitudes 10oE – 75oW. The wind data for forcing the numerical model is obtained from the operational wind analysis of the European Centre for Medium Range Weather Forecast (ECMWF) at 1 hr, 3hrs and 6 hrs resolutions. The variation in significant wave height, peak wave period and peak wave direction obtained from the model for the above three wind inputs have been compared with measured wave data at four sites around Scotland. The results illustrate that the 6 hrs interval wind input agreed well with measurements, however, the relative difference between the wave parameters produced by 1hr, 3 hrs and 6 hrs wind inputs are very small.

182. VIRE A, SPINNEKEN J, PIGGOTT, M.D., PAIN, C.C., KRAMER, S.C. ET AL.: "Application of the immersed-body method to simulate wave–structure interactions", *EUROPEAN JOURNAL OF MECHANICS B-FLUIDS*, *vol. 55*, pp. 330-339, DOI: 10.1016/j.euromechflu.2015.10.001, January–February 2016
This study aims at demonstrating the capability of the immersed-body method to simulate wave–structure interactions using a non-linear finite-element model. In this approach, the Navier–Stokes equations are solved on an extended mesh covering the whole computational domain (i.e. fluids and structure). The structure is identified on the extended mesh through a nonzero solid-concentration field, which is obtained by conservatively mapping the mesh discretising the structure onto the extended mesh. A penalty term relaxes the fluid and structural velocities to one another in the regions covered by the structure. The paper is novel in that it combines the immersed-body method with wave modelling and mesh adaptivity. The focus of the paper is therefore on demonstrating the capability of this new methodology in reproducing well-established test cases, rather than investigating new physical phenomena in wave–structure interactions. Two cases are considered for a bottom-mounted pile. First, the pile is placed in a numerical wave tank, where propagating waves are modelled through a free-surface boundary condition. For regular and irregular waves, it is shown that the wave dynamics are accurately modelled by the computational fluid dynamics model and only small discrepancies are observed in the close vicinity of the structure. Second, the structure is subjected to a dam-break wave impact obtained by removing a barrier between air and water. In that case, an additional advection equation is solved for a fluid-concentration field that tracks the evolution of the air–water interface. It is shown that the load associated with the wave impact on the structure compares well with existing numerical and experimental data.

183. VOKE, M., FAIRLEY, I., WILLIS, M. & MASTERS, I.: "Economic evaluation of the recreational value of the coastal environment in a marine renewables deployment area", *Ocean and Coastal Management*, *vol. 78*, pp. 77-87, DOI: 10.1016/j.ocecoaman.2013.03.013, Jun-13
Marine renewable energy generation (ocean energy) is a growing industry due to global demands for increasing power supplies and reduction in carbon emissions. Intrinsic assets associated with deployment environments and values associated with their existing use need to be established to ensure balanced decisions can be made regarding the sustainable development of marine areas. This paper assesses the value of the marine environment around St. David's, Pembrokeshire, UK, where a tidal stream turbine demonstration project is underway and larger

array developments, both wave and tidal, are planned for the next few years. It was found that the marine environment contributed, on average, to 78% of visitors' total enjoyment of the area. A Contingent Valuation Method (CVM) and Travel Cost Method (TCM) used data collected from questionnaires at the case study site to produce cost and valuation results. The results showed there was a higher revealed preference average value of £148 per person attributed to the area through the Travel Costs incurred by visitors than their stated preference average valuation of £6.70 per person from a willingness to pay CVM contribution. Interviewees were also asked about the potential impact renewable energy generation in the area would have on their visit. Visual aspects of developments and the impact of wave height reduction were queried in particular. Using these responses from interviewees, the influence of marine energy generation in the case study area and the impact on the value of the marine environment was analysed. The results show that only a small number of visitors, 3.5%, would be put off visiting the area again due to marine renewable energy developments. Underwater, non-visible devices were shown to have the least impact on people's enjoyment of the marine environment compared to surface based designs. These results suggest that marine energy developments should not affect tourist revenue.

184. VÖGLER, A. & VENUGOPAL, V.: "Observations on Shallow Water Wave Distributions at an Ocean Energy Site.", *International Conference on Ocean, Offshore and Arctic Engineering, Newfoundland, Canada*, 31 May - 5 June 2015
The paper analyses the changes in wave conditions during wave propagation between intermediate and shallow water depths at a potential wave energy deployment location. The Outer Hebrides of Scotland in the United Kingdom are home to the world’s largest fully consented wave power project and hence a detailed understanding of the local resource is important to the developer to inform annual yield forecasting, technology refinements, and installation and operational plans. To support wave power projects and to reduce uncertainty and risk associated with yield production and performance estimates of energy developments, a sensor network was installed in the area from 2011-2013. Consisting of three floating buoys in intermediate depth and two combined acoustic and pressure sensors in the nearshore region, the data obtained from the different sensors at different locations in close proximity to each other have given a valuable insight in the hydrodynamic wave processes in the area. Data of the two acoustic sensors and one wave buoy are analysed in this paper for a period covering the full range of sea states to be expected throughout a calendar year. Distributions of maximum and significant wave heights, wave steepness and wave direction during a range of different meteorological conditions are examined and a comparison between the different sensor locations is included. The analysis also considers different distributions of both wave power and period observed during the measurement campaign.

185. VÖGLER, A., MORRISON, J., & VENUGOPAL, V.: "An Empirical Analysis of Coastal Shoaling Induced Modifications to Wave Climate and its Impact on Wave Power", *23rd International Offshore and Polar Engineering Anchorage, Alaska*, 30 June - 5 July 2013
This paper presents the results of an analysis carried out to determine the characteristics of waves during the transitional process from intermediate to shallow water off the Isle of Lewis in Scotland. Wave data acquired by a combined wave buoy and ADCP network across an area of approximately 25km x 15km is used for this study which includes three directional wave buoys deployed in 60m depth and two bottom mounted ‘wave enabled’ ADCPs in 12m depth. The study area is targeted for the extraction of wave energy and hence the data analysis concentrates only on the aspects of proportional variation of wave height, energy period and corresponding wave power over a one year period. The results indicate that local shoaling and refraction plays a major role in altering the wave properties and wave power for this region and this is further quantified and discussed in details.

186. VÖGLER, A., VENUGOPAL, V. & ARMSTRONG, D.: "Wave Sensor Observations during a severe Storm event at a Marine Energy Development Site.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
This paper describes observations made by a wave measurement sensor network at a marine energy development area to the west of the outer Hebrides, Scotland. A combination of two directional wave buoys at 60m depth and two seabed mounted wave enabled ADCPs in 13.5m was deployed under the Hebridean Marine Energy Futures project to assist with the calibration and validation of resource assessment studies. The measured datasets include up to two year consecutive shallow water information and about 18 month datasets for intermediate depth. The focus of this paper is on the wave conditions measured during a severe storm even on 04 February 2013, with maximum wave heights larger than 24m. Datasets from the individual sensor locations are compared against each other and the wave transition from intermediate to shallow water is described. Considerable differences in wave parameters observed between both shallow water sensors during the storm are investigated. The spatial distribution of significant wave height across the study site based on a high resolution spectral wave model is also included. Findings described in this study are relevant to wave energy developers and ocean/coastal engineers, as an enhanced understanding of extreme wave properties are provided.

187. WALDMAN, S., MILLER, C., BASTON, S. & SIDE, J.: "Comparison of two hydrodynamic models for investigating energy extraction from tidal flows", *International Conference on Environmental Interactions of*

Marine Renewable Energy Technologies, Stornoway, United Kingdom, 2014
Two commercial suites, MIKE3 by DHI and TideModeller by Ansys, are used to simulate energy extraction by an array of tidal turbines in Lashy Sound, Orkney. We compare the predictions of the two models for the effects of energy extraction on flow speed and water level, and consider the advantages and disadvantages of the two modelling approaches for various environmental impact applications.

188. WALDMAN, S., NEMALIDINNE, R. & BASTON, S.: "Implementation of tidal turbines in hydrodynamic models of Pentland Firth and Orkney Waters", *INORE Symposium, Naples, Italy*, May-15
Regional-scale hydrodynamic modelling has emerged as an essential tool for predicting both the potential performance of tidal stream energy installations, and the environmental impacts that they may have. For the TeraWatt project two industry-standard modelling suites were adopted, as per the guidance of industrial stakeholders. Models of the Pentland Firth and Orkney Waters were built with each package. 950 tidal turbines, representing 1GW of capacity, were inserted into these models using layouts based on information in developers' Environmental Statements. The specification of these turbines was based on a stakeholder workshop. This poster will summarise how the turbines are represented in the models, and present predictions of their physical effects.

189. WALSH, J., THIES, P. R., BASHIR, I., JOHANNING, L., & BLONDEL, P: "Modelling the propagation of underwater acoustic emissions for condition monitoring of marine renewable energy." *2nd International Conference on Renewable Energies Offshore. Lisbon, Portugal.*, 24-Oct-16
Marine Renewable Energy (MRE) has progressed towards commercialisation over the recent years but significant barriers still exist. This includes the currently high cost of energy, leaving MRE uncompetitive with respect to other more established renewable energy technologies. A significant proportion of this cost comes from Operation and Maintenance (O&M) activities. O&M activity can be reduced through the use of condition-based maintenance scheduling. In offshore environments, the submerged location of most devices enables the use of underwater Acoustic Emission (AE), a new condition -monitoring technique. It combines acoustics (used for environmental monitoring of MRE influence on noise levels) with AE condition monitoring as used in air. This paper assesses the practicality of such an approach in complex ocean environments through detailed sound propagation modelling using the propagation model Bellhop in the Matlab toolbox AcTUP. Results show that acoustic propagation is very sensitive to variations in the shallow water environments considered. When concerning sensor placement, multiple-path interferences mean that the location of the measuring sensor(s) needs to be carefully considered, but might not cover all environmental variations over the several months necessary for accurate long-term monitoring. Associated to the shallow depths, these environmental variations also mean that some frequencies cannot be back-propagated easily, generally limiting access to the monitoring of Received Levels. The results presented here are the first steps toward optimizing AE sensor positions and AE measuring strategies for arrays of devices.

190. WANT, A.: "Monitoring Orkney's High-Energy Littoral Environment: Photographic and Image Analysis Methodologies for Quantifying Species and Biotope Coverage", *International Conference on the Environmental Interactions of Marine Renewable Energy Technologies (EIMR), Orkney, Scotland*, 30 April -4 May 2012
The West Mainland shoreline of Orkney is characterised by dramatic sandstone cliffs, complex geomorphologic features including sea stacks and caves, and a few embayments. With a westerly fetch of over 3000 km, wave energy plays a dominant role in both shaping this landscape and determining the ecological community. Access to this considerable wave energy resource has been one of the factors in the recent decision to deploy energy extraction devices off this coastline. We have begun a long-term monitoring programme to assess the consequences of altering wave energy exposure on these rocky shores alongside responses to other systemic forcing agents such as climate change. Within this programme are several photographic surveys including quadrat and fixed view point techniques used to study individual species and biotopes. In addition, we have developed software for economically analysing these images and producing quantitative baseline data on species and biotope coverage.

191. WANT, A., BEHARIE, R.A., BELL, M.C. & SIDE, J.C.: "Baselines and monitoring methods for detecting impacts of hydrodynamic energy extraction on intertidal communities of rocky shores", *Humanity and the Sea*, pp. 21-38, 13-Feb-14
As part of the UK government's objective to deliver an increasing proportion of electricity from renewable sources, West Mainland, Orkney, is at the forefront of the development of wave-energy extraction devices. Exposure to wave energy plays a dominant role in shaping the Orkney landscape and determining the ecological community, but little is known of the consequences of commercial scale removal of energy from the environment. An extensive long-term monitoring programme to assess the impacts of altering wave-energy exposure on these rocky shores alongside responses to other systemic forcing agents such as climate change is continuing. Within the programme are photographic surveys, including quadrat and fixed viewpoint techniques, littoral studies of sentinel species, and the development of cost-effective wave-energy quantifying devices. Software has been developed to

analyse images efficiently, to produce quantitative data on species and biotope coverage. Additionally, extensive surveys along the shoreline provide detailed image records, including areas without prior scientific description, and have helped identify locations of environmental sensitivity. Collectively, the data provide a comprehensive pre-development baseline along this important coast.

192. WANT, A., BELL, M.C. & SIDE, J.: "Baselines and Monitoring Methods for Detecting Impacts of Hydrodynamic Energy Extraction on Intertidal Communities of Rocky Shores.", *Humanity and the Seas: Marine Renewable Energy and Environmental Interactions, Springer*, *ISBN: 978-94-017-8002-5*, 2014
As part of the UK government's objective to deliver an increasing proportion of electricity from renewable sources, West Mainland, Orkney, is at the forefront of the development of wave-energy extraction devices. Exposure to wave energy plays a dominant role in shaping the Orkney landscape and determining the ecological community, but little is known of the consequences of commercial scale removal of energy from the environment. An extensive long-term monitoring programme to assess the impacts of altering wave-energy exposure on these rocky shores alongside responses to other systemic forcing agents such as climate change is continuing. Within the programme are photographic surveys, including quadrat and fixed viewpoint techniques, littoral studies of sentinel species, and the development of cost-effective wave-energy quantifying devices. Software has been developed to analyse images efficiently, to produce quantitative data on species and biotope coverage. Additionally, extensive surveys along the shoreline provide detailed image records, including areas without prior scientific description, and have helped identify locations of environmental sensitivity. Collectively, the data provide a comprehensive pre-development baseline along this important coast.

193. WANT, A., SIDE, J. & BELL, M.C.: "Monitoring high-energy littoral environments: photographic and image analysis methodologies for quantifying species and biotope coverage", *International Council for the Exploration of the Sea (ICES) Annual Science Conference, Bergen, Norway*, 17-21 Sep 2012
Across Europe, governments are setting ambitious targets for delivering energy from renewable sources in attempts to stimulate economic development, promote energy security, and mitigate environmental concerns associated with other energy sources. In the UK, and other maritime nations, wave and tidal energy is playing an increasing role in fulfilling these targets. The west mainland shoreline of Orkney, with a westerly fetch of over 3000 km, is at the forefront in the development of wave energy extraction devices. While exposure to wave energy plays a dominant role in both shaping this landscape and determining the ecological community, little is known of the consequences of removing energy from this environment. We have begun an extensive long-term monitoring programme to assess the impacts of altering wave energy exposure on these rocky shores alongside responses to other systemic forcing agents such as climate change. Within this programme are several photographic surveys, including quadrat and fixed viewpoint techniques used to study individual species and biotopes. We have developed software for efficiently analysing these images and producing quantitative data on species and biotope coverage. In addition, extensive surveys along this shoreline have provided detailed image records and helped to identify areas of environmental sensitivity. Collectively, these data are providing a comprehensive"pre-impact" baseline along this important coastline.

194. WANT, A., SIDE, J.C. & BELL, M.: "Littoral characterisation of west mainland Orkney: the relationship between wave energy, topography and the biological community", *2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR), University of the Highland and Islands, Stornoway, United Kingdom*, 28 April - 2 May 2014
The rocky coast of West Mainland Orkney (WMO) is characterised by spectacular, sheer cliffs shaped by exposure to extreme wave energy and inhabited by a suite of organisms adapted to this challenging environment. As part of the UK government's commitment towards developing the renewable energy sector, in March 2010, the Crown Estate announced the leasing of several sites within this area for development of wave energy extraction. Owing to difficulties of access, the biological communities of much of this coastline have never been adequately described. As part of a long-term monitoring programme, we have incorporated boat-based field methodologies to complete the first comprehensive baseline assessment of the littoral community along the entire rocky shoreline of WMO, extending northeast to beyond Costa Head. Within this assessment are: the wave energy converter (WEC) testing site for the European Marine Energy Centre, at Billia Croo; rocky shores within leasing sites potentially impacted by large-scale WEC deployment and subsea cable installation; and areas distant from potential impacts which are serving as control sites. Data collected includes species abundance and several quantitative and semi-quantitative topographical indices which may mediate wave exposure including slope, aspect, openness and complexity. Additional data have been collected for barnacles, patellid limpets and high-energy variant fucoid algae. Comparable sites on the west coast of Lewis have been surveyed by the team and are included in analyses for comparison.

195. WANT, A., SIDE, J.C. & BELL, M.C.: "The Wild West of Orkney: characterisation of littoral communities along wave-exposed cliff bases", *European Marine Biology Symposium, NUI, Galway, Ireland*, Aug-13

The Wild West of Orkney: characterisation of littoral biotopes along wave exposed cliff bases. The rocky coast of West Mainland, Orkney is characterised by spectacular, sheer cliffs. Exposure to extreme wave energy plays a dominant role in both shaping this landscape and determining the littoral community. In March 2010, the Crown Estate announced the leasing of several sites for development of wave energy extraction. The ecological consequences of commercial scale removal of wave energy, however, are not well understood. As part of a detailed, 'predevelopment' monitoring programme, we have completed the first survey of littoral assemblages along the entire coast of West Mainland, Orkney. This includes description and identification of the biological community along cliff bases and off-shore skerries, a large proportion of which has never previously been surveyed owing to difficulties of access. Biotope coverage was quantified by in situ assessment and by photographic image analysis. Data were also collected on geomorphic features which may mediate wave exposure, such as slope, aspect and complexity of substrate. Survey results suggest that subtle changes in wave exposure can be observed in quantifiable differences in the littoral community which may be of predictive value in identifying changes to the community following long-term environmental change, such as energy extraction. The use of multiple indicators should allow responses to wave energy extraction to be detected alongside a background of changes due to other systemic forcing agents such as climate change.

196. WILLIS, M.R., BROUDIC, M. & MASTERS, I.: "Ambient underwater noise in high and low energy flow conditions", *International Conference on Wind Turbine Noise, National Research Council of Italy, Rome, Italy*, 11-14 April 2011

The planned order-of-magnitude expansion of the UK offshore wind industry coupled with ambitious wave, tidal stream and tidal range projects over the next 20-30 years will undoubtedly lead to an increase in noise associated with the installation, operation and decommissioning of these devices. Before these potential effects can be quantified, the background noise needs to be characterised with regard to its constituent frequency bands and the anthropogenic/natural origins of the noise source. This paper presents the results of background noise measurements at two near-shore sites along the Welsh Coast. One site is subject to tidal currents up to 2 m.s-1 during spring tides and has a resident population of harbour porpoise in close proximity. The other is relatively sheltered with tidal flows around 1 $m.s^{-1}$ and is close to a transient population of harbour porpoise. The problems associated with taking hydrophone readings in high tidal, turbulent currents are discussed. The influences that tidal environment and shipping activity have on background noise are also discussed. This paper presents the underwater background noise difference (levels, frequencies) between offshore wind site (low energy flow) and tidal/wave energy site (high energy flow). Using the Power Level (PL) in dB re 1 mPa and sound pressure level (SPL) in root mean square (dB re 1 mParms in 1/3rd Octave band), this paper establishes the underwater background noise comparison of two different energy sites as a function of the tide, boat traffic and current speed. It has been found that the low frequency response of underwater background noise at high and low energy sites were similar. Both sites showed increases in sound pressure levels (SPL) around 1-20 Hz although the extent of the increase varied with tidal speed and weather conditions. The importance of characterising background noise (and subsequent operational noise) across the spectra of frequencies is emphasised. Background noise levels are normally reported as root mean squared values whereas operational noise is measured as zero-to-peak or peak-to-peak. The authors stress that whenever noise measurements are presented that the methodology and units should be stated to avoid misunderstanding.

197. WILLIS, M.R., BROUDIC, M., HAYWOOD, C., MASTERS, I. & THOMAS, S.: "Measuring underwater background noise in high tidal flow environments", *Renewable Energy*, *vol. 49*, pp. 255-258, DOI: 10.1016/j.renene.2012.01.020, Jan-13

Understanding the effect of marine energy development on the underwater noise levels in a proposed installation area forms a crucial part of any Environmental Impact Assessment. This paper uses boat-based hydrophone survey data taken from an area subject to tidal currents up to 3 ms^{-1} and determines how the background noise levels change with tidal flow and flow direction. It was found that a more meaningful expression of background noise was gained by reference to "Power level" as measured by the Root Mean Square of the spectrum. Hydrophone measurements were taken during low season (with respect to other maritime activity) and in high season over the entire tidal cycle. Background noise levels ranged between 72 and 108 dB re 1 µPaRMS with higher sound pressure levels occurring at frequencies below 100 Hz. Background noise levels increased with increasing tidal flow and were higher on ebb tides than flood tides.

198. WILLIS, M.R., BROUDIC, M., MASTERS, I.: "A comparison of underwater noise at two high energy tidal stream sites", *EWTEC 2011, Southampton, UK*, Sep-11

The amount of noise associated with the installation, operation and decommissioning of tidal stream devices and the effect that this noise has on the resident and transient marine wildlife populations is a prime concern of the marine energy stakeholder community. Before assessing the potential impact that a marine energy device may have on the environment, it is crucial to characterise underwater background noise as a baseline of a marine

energy project. This paper considers the ambient noise associated with anthropogenic noise at two sites typical of hosting tidal stream turbines in the future. The first site is an open channel measuring approximately 2.5 km long by 1 km wide, varying in depth between 25 and 70 m referring to the Lowest Astronomic Tides (LAT) and subject to tidal streams in excess of 3 $m.s^{-1}$. The second site is an inlet channel, 1.5 km long by 200 m wide, between 2 and 10 m LAT and again experiencing flows of around 3 $m.s^{-1}$ during spring tides. Anthropogenic noise occurred during the recordings: intense boat traffic (first site), pile driving and vibro-drilling (second site). The impact that these anthropogenic noises may have on ambient noise in shallow water are quantified and discussed.

199. WOOLF, D. & WOLF, J.: "Impacts of climate change on storms and waves", *MCCIP Science Review 2013*, pp. 20-26, DOI: 10.14465/2013.arc03.020-026, 2013
There is a history of strong variability in UK wave climate. Inter-annual variability in the modern wave climate is strongest in the winter and can be related to atmospheric modes of variability, most notably the North Atlantic Oscillation. Rather dramatic increases in wave height occurred between 1960 and 1990, but these are now seen as just one feature within a longer history of variability. There is no clear pattern in results since 1990. Natural variability in wave climate is strong and the role of anthropogenic forcing is uncertain. There is as yet no consensus on the future storm and wave climate, stemming from diverse projections of future storm track behaviour, but new projections using the latest generation of climate models, under CMIP5 have yet to be fully assessed.

200. WRIGHT, R.M, NEILL, S.P. & JENKINS, S.R.: "Renewable energy structures as stepping-stones in the connectivity and dispersal of marine benthic organisms", *2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR), University of the Highland and Islands, Stornoway, United Kingdom*, 28 April - 2 May 2014
Marine renewable energy is a rapidly expanding global sector, which will significantly increase the amount of artificial substrate in the marine environment, often introducing hard substrate to areas of sand/mud. Marine renewable energy structures (MRES) act as artificial reefs, particularly for hard bottom sessile species by providing additional settlement sites for larvae. This has the possibility to alter population connectivity and dispersal, potentially facilitating invasion by non-indigenous species. The potential of MRES to act as 'stepping-stones' is investigated by modelling larval dispersal of benthic organisms in an area with a high number of MRES in planning, the Pentland Firth and Orkney Waters, North Scotland.

201. YATES, N., WALKINGTON, I.A., BURROWS, R. & WOLF, J.: "Appraising the Extractable Tidal Energy Resource of the UK's Western Coastal Waters", *Phil Trans R Soc A*, *vol. 371*, *issue. 1985*, 2013
A two-dimensional west coast tidal model, built on the ADCIRC platform (an unstructured grid two-dimensional depth-integrated shallow water model), has been developed to examine the scope for reliable and fully predictable electricity generation from UK coastal waters using an ambitious combination of estuary barrages, tidal lagoons and tidal stream generator arrays. The main emphasis has been towards conjunctive operation of major estuary barrages, initially including the presence of pilot-scale tidal stream developments, though ambitious exploitation of extensive tidal streams has also been explored.

202. YIN, Y., LI, M., MOULINEC, C. & EMERSON, D.: "3D modelling morphological impact of offshore wind farms using LES model on HPC", *34th International conference on Coastal Engineering, ASCE, Seoul, Korea*, 15-20 June 2014
A model based on TELEMAC 3D using Large Eddy Simulation has been developed to simulate of complex flows and sediment transport around offshore wind farm foundations. The model was tested against available laboratory experimental data with satisfactory agreement. The model results reveal that with fine resolution, using Large Eddy Simulation allows to capture the turbulence eddy shedding behind the structure better than using conventional RANS models. Application of the model to the Burbo Bank OWF in Liverpool Bay, in North West England helps capturing the strong 3D structures across the depth, which can have considerable influence on sediment suspension and transport around the structure, particularly for fine sediments.

203. ZACHARIOUDAKI, A. & REEVE, D.E.: "Shoreline evolution under climate change wave scenarios", *Climatic Change*, *vol. 108*, *issue. 1*, pp. 73-105, DOI: 10.1007/s10584-010-0011-7, Sep-11
This paper investigates changes in shoreline evolution caused by changes in wave climate. In particular, a number of nearshore wave climate scenarios corresponding to a 'present' (1961–1990) and a future time-slice (2071–2100) are used to drive a beach evolution model to determine monthly and seasonal statistics. To limit the number of variables, an idealised shoreline segment is adopted. The nearshore wave climate scenarios are generated from wind climate scenarios through point wave hindcast and inshore transformation. The original wind forcing comes from regional climate change model experiments of different resolutions and/or driving global climate models, representing different greenhouse-gas emission scenarios. It corresponds to a location offshore the south central coast of England. Hypothesis tests are applied to map the degree of evidence of future change in wave and shoreline statistics relative to the present. Differential statistics resulting from different global climate models and

future emission scenarios are also investigated. Further, simple, fast, and straightforward methods that are capable of accommodating a great number of climate change scenarios with limited data reduction requirements are proposed to tackle the problem under consideration. The results of this study show that there are statistically significant changes in nearshore wave climate conditions and beach alignment between current and future climate scenarios. Changes are most notable during late summer for the medium-high future emission scenario and late winter for the medium-low. Despite frequent disagreement between global climate change models on the statistical significance of a change, all experiments agreed in future seasonal trends. Finally, a point of importance for coastal management, material shoreline changes are generally linked to significant changes in future wave direction rather than wave height.

204. ZANGIABADI. E., MASTERS, I., WILLIAMS, A.J. & CROFT, T.N.: "Characterisation of the Coastal Hydrology of Oceans Using 3D Computational Fluid Dynamics", *Fourth International Conference on Ocean Energy (ICOE), Dublin, Ireland*, 17-19 Oct 2012
Knowing the characteristics of the current is necessary in order estimate the energy a tidal stream turbine (TST) could extract from a site. These characteristics are strongly influenced by the topography of the seabed. Often in locations of fast currents, which are ideal sites for TSTs, there is significant detail in the bathymetry. Modelling of the flow in an estuary or a channel therefore offers a challenge as a large domain is required to reduce the influence of the boundary assumptions but this leads to problems resolving the effects of the bathymetry on the flow and turbulence. This paper describes a computational fluid dynamics model of a potential TST deployment site. The bathymetry of the deployment site was surveyed using an echosounder and the resulting data was used in the development of the geometric detail. Two different turbulence models (k-e and LES) were investigated and the simulation results were then compared with the flow data gathered by Acoustic Doppler Current Profiler (ADCP) survey. Despite some simplifications in the model, the result showed good agreement with the real site data.

205. ZANGIABADI, E., MASTERS, I., WILLIAMS, A.J., CROFT, T.N., MALKI, R., EDMUNDS, M., MASON-JONES, A. & HORSFALL, I.: “Computational prediction of pressure change in the vicinity of tidal stream turbines and the consequences for fish survival rate” *Renewable Energy, vol. 101,* pp. 1141-1156, ISSN 0960-1481, http://dx.doi.org/10.1016/j.renene.2016.09.063. Feb 2017
The presence of Tidal Stream Turbines (TST) for tidal power production, leads to changes in the local physical environment that could affect fish. While other work has considered the implications with respect to conventional hydroelectric devices (i.e. hydroelectric dams), including studies such as physical impact with the rotors and pressure variation effects, this research considers the effects of sudden changes in pressure and turbulence on the hypothetical fish with respect to TSTs. Computational fluid dynamics (CFD) is used to investigate changes to the environment, and thus study the implications for fish. Two CFD methods are employed, an embedded Blade Element representation of the rotor in a RANS CFD model, and a blade resolved geometry using a moving reference frame. A new data interpretation approach is proposed as the primary source of environmental impact data; ‘rate of change of pressure’ with time along a streamtrace. This work also presents results for pressure, pressure gradients, shear rates and turbulence to draw conclusions about changes to the local physical environment. The assessment of the local impact is discussed in terms of the implications to individual fish passing a single or array of TST devices.

Extreme Loadings and Durability

207. AFGAN, I., MCNAUGHTON, J., ROLFO, S., APSLEY, D.D., STALLARD, T. & STANSBY, P.K.: "Turbulent flow and loading on a tidal stream turbine by LES and RANS", *International Journal of Heat and Fluid Flow*, *vol. 43*, pp. 96-108, DOI: 10.1016/j.ijheatfluidflow.2013.03.010, 17-Jun-13
This paper presents results from numerical simulations of a 3- bladed horizontal axis tidal stream turbine. Initially, Reynolds Averaged Navier Stokes (RANS) k- ω Shear Stress Transport eddy-viscosity and Launder-Reece-Rodi models were used for code validation and testing of a newly implemented sliding mesh technique for an unstructured finite volume code. Wall- and blade-resolved large-eddy simulations (LES) were then performed to study the complete geometry at various tip speed ratios (TSR). Thrust and power coefficients were compared to published experimental measurements obtained from a towing tank for a range of TSR (4, 5, 6, 7, 8, 9 & 10) at a fixed hub pitch angle. A strong meandering is observed downstream of the supporting tower due to interaction between the detached tip vortices and vortex shedding from the support structure. The wake profiles and rate of recovery of velocity deficit show high sensitivity to the upstream turbulence intensities. However, the mean thrust and power coefficients were found to be less sensitive to the upstream turbulence. Comparisons between RANS and LES are also presented for the mean sectional blade pressures and mean wake velocity profiles. The paper also presents an overview of modelling and numerical issues relating to simulations for such rotating geometries.

208. AGARWAL, A., VENUGOPAL, V. & HARRISON G.P.: "The assessment of extreme wave analysis methods applied to potential marine energy sites using numerical model data", *Renewable and Sustainable Energy Reviews*, *vol. 27*, pp. 244-257, DOI: 10.1016/j.rser.2013.06.049, 2013
The accurate estimation of extreme conditions, such as 100-yr return levels of significant wave height is an important aspect in the design of marine energy converters, offshore and coastal structures. This study investigates the different approaches for the estimation of extreme waves that have been applied in the past, and determines the 100-yr return levels using the high resolution ERA-Interim dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). It is demonstrated in the paper that fitting a Generalized Pareto Distribution to all exceedances over a high threshold is the most suitable approach. The estimates thus obtained are compared with previously computed estimates for buoys and offshore platforms. The effect of duration of data on the estimates is also investigated. Finally, a 100-yr return level map for the North Atlantic region is presented.

209. AHMED, U., AFGAN, I., APSLEY, D., STALLARD, T. & STANSBY,. P.K.: "CFD Simulations of a Full-Scale Tidal Turbine: Comparison of LES and RANS with Field Data.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
CFD simulations have been performed for a geometry-resolved full-scale tidal-stream turbine and compared with experimental data from the EMEC test site in the Orkney Isles. The mesh comprises two regions: a rotating part, containing the turbine, and a stationary outer part, including the support tower. A sliding-mesh interface couples the two parts.Initially, Reynolds-averaged Navier-Stokes and large-eddy simulations were performed using an inflow velocity profile representative of the test site but low inflow turbulence, yielding satisfactory mean power coefficients. LES with synthetic turbulence prescribed at inlet was then employed to try to predict realistic load fluctuations. Load fluctuations (power, thrust and blade bending moments) may arise from onset mean velocity shear, influence of the support tower, blade-generated turbulence, approach-flow turbulence and waves. Inflow statistics were prescribed to match the vertical distribution of mean velocity, Reynolds stresses and length scales determined from a channel-flow simulation, with additional factoring of stresses and length scales to match as far as possible those measured on-site. LES simulations with synthetic turbulence at inflow satisfactorily reproduces the spectral distribution of blade bending moments provided that spectra are normalised by variance to reflect the relatively small number of rotations computed.

210. AHMED, U., APSLEY, D., STALLARD, T., AFGAN, I. & STANSBY, P.K.: "Large Eddy Simulations to represent a full scale tidal stream flow and turbine", *Oxford Tidal Energy Workshop, Oxford, United Kingdom*, 23-24 March 2015
CFD simulations are performed to represent the depth profile of velocity and turbulence measured at the deployment site of a full-scale tidal stream turbine to assess blade load predictions. Turbulent inflow conditions are defined using a Synthetic Eddy Method [1] based on precursor periodic channel simulations and with scaling applied to represent field measurements. The geometry of rotor and nacelle represent the 18 m diameter Alstom Ocean 1 MW tidal stream turbine. Simulations are conducted using Code_Saturne using a sliding mesh procedure [2]. LES simulations of a channel flow have also been conducted to determine the conditions incident to the rotor during operation. Turbulent kinetic energy spectra and instantaneous blade loads are compared for alternative inflow conditions and with field data.

211. ALLSOP, S., PEYRARD, C., & THIES, P. R.: "A BEMT model for a high solidity, hubless and ducted tidal stream turbine.", *5th Oxford Tidal Energy Workshop. Oxford, UK.*, Mar-16

A Blade Element Momentum Theory (BEMT) model for 'conventional' 3 bladed designs of Tidal Stream Turbine (TST) is presented, with validations from scale model experiments carried out in a cavitation tunnel. Assumptions and limitations of the model are discussed in order to gauge potential use in assessing a high solidity, hubless and ducted TST design, which has been developed by OpenHydro. A number of adjustments to the model are considered, which are to be validated with fully blade resolved CFD studies and field data from a full scale device deployed at Paimpol-Bréhat, Brittany at the start of 2016 in collaboration with EDF.

212. ANTONUTTI, R., PEYRARD, C., JOHANNING, L., INCECIK, A. & INGRAM, D.: "An investigation of the effects of wind-induced inclination on floating wind turbine dynamics: heave plate excursion", *Ocean Engineering*, *vol. 91*, pp. 208-217, DOI: 10.1016/j.oceaneng.2014.09.008, 15-Nov-14
A current trend in offshore wind is the quest for exploitation of ever deeper water sites. At depths between 50 m and 100 m a promising substructure is the column-stabilised semi-submersible floating type. This solution is currently being tested at full scale at the WindFloat and Fukushima Forward demonstrator sites in Portugal and Japan respectively. The semi-sub design class frequently adopts passive motion control devices based on the water entrapment principle, such as heave plates, tanks, and skirts. Whilst effective for small inclinations, these can underperform when the structure is inclined under wind loading. This study examines the alteration of potential hydrodynamics due to wind-induced trim (geometric non-linearity) and its impact on the wind turbine's wave response with focus on heave plate performance. Firstly it is shown by using the boundary element approach that wind trim affects wave loading in the ocean wave band between 5 s and 15 s, and introduces hydrodynamic coupling typical of non-symmetric hulls. These features are incorporated in frequency-domain dynamic response analysis to demonstrate that said effects bear a significant impact on the turbine's motion in waves. Accounting of heave plate excursion improves the assessment of the seaworthiness of floating wind turbine concepts, potentially leading to new design constraints.

213. BASTON, S., HARRIS, R.E., WOOLF, D.K., HILEY, R.A. & SIDE, J.: "Sensitivity Analysis of the Turbulence Closure Models in the Assessment of Tidal Energy Resource in Orkney", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Orkney is at the forefront of the development of marine renewable technologies and ocean energy exploitation.Since different technologies to harness energy from the tide would be located at different depths of the water column, 3-D simulations should be more appropriate than 2-D to predict effects on the environment. In 3-D simulations the vertical turbulent eddy viscosity and turbulent diffusivity are computed using a turbulence closure model. In this paper a sensitivity analysis of the turbulence closure models included in Delft3D is presented. Comparison of the model results against ADCP data deployed in the Pentland Firth shows that the model reproduces the general hydrodynamics of the study area. Tidal races are however over-predicted by the model up to 1 m/s in spring tides. A shape analysis of the velocity profiles has been conducted,indicating that a $1/5^{th}$ law would appear to be a better description of the ADCP data analysed in this study than a more standard 1/7 law. The observed profiles in the Pentland Firth, where currents are many times greater than most earlier study sites, justifies the careful attention to vertical profiles using a 3D model. A satisfactory turbulence closure scheme for the 3Dmodel cannot yet be identified with confidence.

214. BLACKMORE, T., BATTEN, W.M.J. & BAHAJ, A.S.: "Inlet grid-generated turbulence for large-eddy simulations", *International Journal of Computational Fluid Dynamics*, *vol. 27*, *issue. 06-Jul*, pp. 307-315, DOI: 10.1080/10618562.2013.819972, Jul-13
A new technique of generating turbulence in large-eddy simulations LES has been investigated and results compared with previous studies for validation. The proposed gridInlet technique uses a grid pattern on the inlet boundary patch to produce grid-generated turbulence as used in wind tunnel experiments. This allows the turbulence integral length scale to be controlled by changing the grid size, while the turbulence intensity is controlled by changing the inlet distance. The objective of this paper is to investigate domain and mesh requirements to implement the gridInlet technique. This technique is most suited to studies on the influence of high-intensity isotropic turbulence on objects, particularly if comparisons are to be made to experimental data obtained with grid-generated turbulence.

215. BLACKMORE, T., BATTEN, W.M.J., MÜLLER, G.U. & BAHAJ, A.S.: "Influence of turbulence on the drag of solid discs and turbine simulators in a water current", *Experiments in Fluids*, *vol. 55*, *issue. 1637*, 2014
Laboratory experiments have been used to investigate the effects of turbulence on the drag of both solid discs and porous disc turbine simulators. These discs were introduced to turbulent flows, in a gravity-fed water flume, with various levels of turbulence intensity and integral length scales. The turbulence was generated using three different grid configurations, which produced intensities and scales comparable with previous wind tunnel studies. The drag measurements were taken with discs of two different diameters and porosities with and without the upstream grids. The experimental results have demonstrated that the drag coefficients, of all the discs tested, are significantly dependent on both the turbulence intensity and integral length scale. For small integral length scales,

relative to the disc, the drag coefficients converged for turbulence intensities greater than 13 %, with an increase of around 20 % in drag coefficient over the low-intensity case. Experiments with turbulence intensities of 10 % demonstrated minimum drag coefficients when the integral length scale-to-disc diameter ratio was around 50 %. Significant variations in the drag coefficient of circular bluff bodies are therefore expected when operating in turbulent flows with different characteristics.

216. BOUFERROUK, A., HARDWICK, J.P., COLUCCI, A.M. & JOHANNING, L.: "Quantifying turbulence from field measurements at a wave energy site", *Renewable Energy*, *vol. 87*, *issue. 1*, pp. 478–492, DOI: http://dx.doi.org/10.1016/j.renene.2015.10.046, Mar-16
This study explores typical characteristics of the mean and turbulent profiles at a mixed low tidal energy site (40 m mean water depth) where the waves have limited effects on the currents. The turbulence profiles were derived from secondary current data using a 5-beam ADCP which was optimised for wave measurements. The tidal currents have peak flows of ~1 m/s during spring tide. The turbulence intensity is no less than 10% at peak flows and compares well with values at other tidal channels (at ~5 m from seabed). The Reynolds stresses show symmetry at the neap tide but less so for the spring tide. Although the qualitative profiles of TKE are similar between the neap and spring tides, the values of TKE for flood flow are the largest throughout the deployment. The integral length scales are in good agreement with theory, and with estimates based on the mixing length concept. The measured turbulence parameters are sensitive to flow inhomogeneity, Doppler noise, and ADCP tilt. The findings demonstrate the practical benefits of exploiting secondary current data at a mixed low tidal energy site for estimating typical turbulence characteristics; such information can be used to define design standards and protocols for marine energy devices.

217. BUCKLAND, H.C., MASTERS, I., & ORME, J.: "Wave Implementation in Blade Element Momentum theory for modelling tidal stream turbines", *In Proceedings of the 19th UK conference of the Association for Computational Mechanics in Engineering, Edinburgh, UK*, 2011
A study of the non-linear and three-dimensional effects of a regular wave incident on a tidal turbine using Blade Element Momentum Theory and Chaplins stream function wave theory. BEMT is a method of modelling the performance of wind and marine turbines by combining one-dimensional momentum theory with rotational momentum and blade element theory. Chaplin’s stream function uses linear wave theory in a moving frame of reference to describe an incident wave front. The limitations and compatibility of BEMT and the stream function theory are discussed. Results for a freely rotating turbine are presented in the frequency, time and Tip Speed Ratio (TSR) domains. The turbine data used has been validated against tank testing by Bahaj et al.[1] and the Garrad Hassan Tidal Bladed software [6].

218. BULDAKOV, E., STAGONAS, D. & SIMONS, R.: "Lagrangian Numerical Wave-Current Flume", *International Workshop on Water Waves and Floating Bodies, Bristol, United Kingdom*, 12-15 April 2015
Lagrangian formulation for surface waves with vorticity is used to create a numerical wave-current flume. The numerical flume is then used to reproduce a physical experiment on focused wave groups in sheared currents. The numerical results include evolution of the free surface of focused wave groups in still water and over in-line and opposing currents and flow kinematics under such waves. Numerical results are compared with experiment and demonstrate good agreement.

219. CHAPMAN, J.C., MASTERS, I., TOGNERI, M. & ORME, J.A.C.: "The Buhl correction factor applied to high induction conditions for tidal stream turbines", *Renewable Energy*, pp. 472-480, DOI: 10.1016/j.renene.2013.05.018, 2013
Blade Element Momentum Theory (BEMT) is a computationally efficient method of calculating the performance of a tidal stream turbine (TST) generating energy from the ocean. This efficiency is achieved by making several simplifying assumptions; an unintended consequence of these assumptions is the omission of some phenomena that can significantly alter the performance and loads of a TST. We can ameliorate this by incorporating suitable corrections into a BEMT model, which allow us to account for some of the effects of these phenomena. This paper examines the implementation of corrections in an established BEMT solver for two such phenomena: tip/hub losses and high induction conditions.Tip losses are attributable to the flow of fluid around end of the blade, a flow feature omitted in the classical BEMT treatment of turbines. At high tip speed ratios, above the designed operating range of the device, the theory based on an axial interference factor, a, diverges from experimental results and, indeed, becomes physically untenable. Buhl proposed a high induction correction factor for wind turbines operating in air and a modified version of his correction is implemented here for a TST operating in water. The tip/hub loss and high-induction corrections are well-integrated with one another. The validity of the high-induction correction is checked against experimental results; we find that our model predicts power output well but overpredicts axial thrust compared to laboratory observations.

220. CHEN, L.F., ZANG, J., HILLIS, A.J., MORGAN, G.C.J. & PLUMMER, A.R.: "Numerical investigation of wave–structure interaction using OpenFOAM", *Ocean Engineering*, *vol. 88*, pp. 91-109, DOI: 10.1016/j.oceaneng.2014.06.003, 15-Sep-14
The present work is focused on the assessment of how OpenFOAM performs when applied to non-linear wave interactions with offshore structures for ranges of wave conditions. New modules have been further extended to advance the wave generation and wave absorbing capabilities of the code. The numerical results for wave interactions with a vertical surface piercing cylinder have been compared with physical experiments performed at Danish Hydraulic Institute (DHI). Comparisons between the numerical results and the measured data for three regular waves and four focused wave groups, have indicated that OpenFOAM is very capable of accurate modelling of nonlinear wave interaction with offshore structures, with up to 4th order harmonic correctly captured. Moreover, by using the crest-trough phase-based separation method, we can reproduce harmonic structure in the wave loading on the structure and free surface elevations.

221. DE JESUS HENRIQUES, T.A., HEDGES, T.S., OWEN, I. & POOLE, R.J.: "Influence of Blade Pitch Angle on the Performance of Horizontal Axis Tidal Stream Turbines Subject to Wave-Current Interaction", *Energy*, pp. 166-175, DOI: 10.1016/j.energy.2016.02.066, May-16
Tidal stream turbines offer a promising means of producing renewable energy at foreseeable times and of predictable quantity. However, the turbines may have to operate under wave-current conditions that cause high velocity fluctuations in the flow, leading to unsteady power output and structural loading and, potentially, to premature structural failure. Consequently, it is important to understand the effects that wave-induced velocities may have on tidal devices and how their design could be optimised to reduce the additional unsteady loading. This paper describes an experimental investigation into the performance of a scale-model three-bladed HATT (horizontal axis tidal stream turbine) operating under different wave-current combinations and it shows how changes in the blade pitch angle can reduce wave loading. Tests were carried out in the recirculating water channel at the University of Liverpool, with a paddle wavemaker installed upstream of the working section to induce surface waves travelling in the same direction as the current. Three wave conditions were employed in a current-dominated flow. The wave kinematics were measured using an acoustic Doppler velocimeter and there was generally good agreement with Stokes' second-order wave theory. Power and thrust measurements were taken under both current-alone and wave-current conditions for different blade pitch angles. It was observed that, as the blade pitch angle was increased from optimum, both the mean power and thrust on the turbine decreased and the reductions in thrust were always greater than in power. The fluctuations in power and thrust also decreased with an increase in the blade pitch angle. Therefore, changes in blade pitch angle can be used as a mechanism for reducing the loading on a HATT when operating with excessive wave-induced loads, while still enabling a significant amount of the available power in the unsteady tidal stream to be extracted.

222. DOMAN, D.A., GRACIE, K., JOHNSTONE, C.M., MURRAY, R.E., PEGG, M.J. & NEVALAINEN, T.: "Dynamic testing of a 1/20th scale tidal turbine", *2nd Asian Wave and Tidal Energy Conference, Japan*, 28 July - 1 Aug 2014
Passively adaptive tidal turbine rotors provide effective power regulation and load mitigation, yet avoid the complexity and vulnerabilities associated with variable pitch mechanisms and the high loads and electro-magnetic capacity required for passive stall regulation. This paper presents experimentally derived performance data of a three-bladed 1/20th scale NREL S814 horizontal axis tidal turbine. This data establishes a baseline from which blades designed for passive rotor control are being developed. Further, the development and initial verification of a BEMT code is used.

223. ELASHA, F., GREAVES, M. & MBA, D.: "A comparative study of the effectiveness of vibration and acoustic emission in diagnosing a defective bearing within a planetary gearbox", *Journal of Vibration and Acoustic, ASME*
Whilst vibration analysis of planetary gearbox faults is relatively well established, the application of Acoustic Emission (AE) to this field is still in its infancy. For planetary-type gearboxes it is more challenging to diagnose bearing faults due to the dynamically changing transmission paths which contribute to masking the vibration signature of interest. The present study is aimed to reduce the effect of background noise whilst extracting the fault feature from AE and vibration signatures. This has been achieved through developing of internal AE sensor for planetary transmission system. In addition, series of signal processing procedure has been developed to improved detection of incipient damage. Three signal processing techniques including an adaptive filter, spectral kurtosis and envelope analysis, were applied to AE and vibration data acquired from a simplified planetary gearbox test rig with a seeded bearing defect. The results show that AE identified the defect earlier than vibration analysis irrespective of the tortuous transmission path.

224. ELASHA, F., GREAVES, M. & MBA, D.: "Diagnostics of a defective bearing within a planetary gearbox with vibration and acoustic emission", *International Conference on Condition Monitoring of Machinery in Non-Stationary Operations, Lyon, France*, DOI: 10.13140/RG.2.1.4553.8642, 15-16 Dec 2014
Whilst vibration analysis of planetary gearbox faults is relatively well established, the application of Acoustic

Emissions (AE) to this field is still in its infancy. For planetary-type gearboxes it is more challenging to diagnose bearing faults due to the dynamically changing transmission paths which contribute to masking the vibration signature of interest. The present study is aimed at developing a series of signal processing proce-dures to reduce the effect of background noise whilst extracting the fault feature from AE and vibration signatures. Three signal processing techniques including an adaptive filter, spectral kurtosis and envelope analysis, were applied to AE and vibration data acquired from a simplified planetary gearbox test rig with a seeded bearing defect. The results show that AE identified the defect earlier than vibration analysis irrespective of the tortuous transmission path.

225. ELASHA, F., MBA, D. & TEIXEIRA, J.A.: "Gearboxes Prognostics With Application To Tidal Turbines", *International Conference on Condition Monitoring and Machinery Failure Prevention Technologies, Oxford, United Kingdom*, DOI: 10.13140/RG.2.1.4226.1840, 9-11 June 2015
Although premature gearbox failures have plagued the wind turbine industry, and considerable research efforts continue to address this challenge, tidal turbine gearboxes are expected to experience higher mechanical failure rates given they will experience higher torque and thrust forces. In order to minimize the maintenance cost and prevent unexpected failures there exists a fundamental need for prognostic tools that can reliably estimate the current health and predict the future condition of the gearbox. This paper presents a life assessment methodology for tidal turbine gearboxes which was developed with synthetic data generated using a blade element momentum theory (BEMT) model. The latter has been used extensively for performance and load modelling of tidal turbines. The prognostic model developed was validated using experimental data.

226. ELASHA, F., MBA, D. & TEIXEIRA, J.A.: "Establishment of condition based maintenance for Tidal Turbines", *Condition Monitoring and Diagnostic Engineering Management conference, Brisbane, Australia*, DOI: 10.13140/RG.2.1.4881.5443, 2014
In order to ensure safe operation and prolonged life for tidal turbines, condition monitoring is essential. The technology for power generation using tidal turbines is new therefore the condition monitoring concept for these devices is yet to be established. Also there is a lack of understanding of techniques suitable for health monitoring of the turbine components and support structure given their unique operating environment. In this paper the condition monitoring of a tidal turbine is investigated. The objective is to highlight the need for condition monitoring and establish procedures to decide the condition monitoring techniques required to establish efficient condition based maintenance.

227. ELASHA, F., MBA, D., & RUIZ-CARCEL, C.: "Bearing natural degradation detection in a gearbox: A comparative study of the effectiveness of adaptive filter algorithms and spectral kurtosis", *ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis, Copenhagen, Denmark*, 25-27 June 2014
Bearing faults detection at the earliest stages is vital in avoiding future catastrophic failures. Many traditional techniques have been established and utilized in detecting bearing faults, though, these diagnostic techniques are not always successful when the bearing faults take place in gearboxes where the vibration signal is complex; under such circumstances it may be necessary to separate the bearing signal from the complex signal. The objective of this paper is to assess the effectiveness of an adaptive filter algorithms compared to a Spectral Kurtosis (SK) algorithm in diagnosing a bearing defects in a gearbox. Two adaptive filters have been used for the purpose of bearing signal separation, these algorithms were Least Mean Square (LMS) and Fast Block LMS (FBLMS) algorithms. These algorithms were applied to identify a bearing defects in a gearbox employed for an aircraft control system for which endurance tests were performed. The results show that the LMS algorithm is capable of detecting the bearing fault earlier in comparison to the other algorithms.

228. ELASHA, F., MBA, D., KILUNDU, B. & OMPUSUNGGU, A.P.: "Effect of parameters setting on performance of discrete component removal (DCR) methods for bearing faults detection", *European Conference of the Prognostics and Health Management Society, Nantes, France*, 8-10 June 2014
Detecting bearing faults on rotating machinery based on vibration signals is often a challenge due to the high energy (dominant) signals originating from gears, screws, and/or shafts that can mask weak signal (i.e. non-deterministic) generated by bearing faults. These dominant signals are deterministic, meaning that they will appear as discrete components in the frequency domain. When bearing faults detection is of interest, it is therefore important to remove these discrete components prior to applying further signal processing. Several methods have been proposed in literature for separating discrete components and non-deterministic components (i.e. residual signals) useful for bearing fault detection. The choice of setting parameters when applying these methods can have a significant effect on the residual signals. This paper compares the performance of bearing fault detection after applying different DCR methods. Here, three methods are evaluated, namely synchronous average, synchronous adaptive noise cancellation and cepstrum editing. A qualitative comparison of different methods has also been recently performed by Randall et al. However, to the authors' knowledge, the effects of different parameters setting on the performance of bearing fault detection have not discussed yet elsewhere. To fill this gap, this paper aims at discussing the effects of parameters setting and eventually providing a quantitative

comparison. In cepstrum editing, the width of the notch “lifter” is an important parameter. When using TSA to separate non- and deterministic components, the case of a multiple shafts situation, the number of averages as well as the quality of the tachometer signal have to be considered. For demonstration purposes, these three methods have been applied for bearing faults detection on vibration signals measured on two gearboxes, namely (i) a laboratory gearbox used in PHM09 data competition and (ii) an industrial gearbox which is a part of a transmission driveline on the actuation mechanism of secondary control surface in civil aircraft. The residual signals from these 3 methods are processed following the optimized envelope analysis by using spectral kurtosis for determining the optimal frequency band for demodulation. Synchronous adaptive noise cancellation gives acceptable results. Cepstrum editing results in the best separation.

229. ELASHA, F., RUIZ-CARCEL, C., MBA, D. & CHANDRA, P.: "A Comparative Study of the Effectiveness of Adaptive Filter Algorithms, Spectral Kurtosis and Linear Prediction in Detection of a Naturally Degraded Bearing in a Gearbox", *Journal of Failure Analysis and Prevention*, *vol. 14*, *issue. 5*, pp. 623-636, DOI: 10.1007/s11668-014-9857-8, 2014
Diagnosing bearing faults at the earliest stages is critical in avoiding future catastrophic failures. Many techniques have been developed and applied in diagnosing bearings faults; however, these traditional diagnostic techniques are not always successful when the bearing fault occurs in gearboxes where the vibration response is complex; under such circumstances, it may be necessary to separate the bearing signal from the complex signal. In this paper, an adaptive filter has been applied for the purpose of bearing signal separation. Four algorithms were compared to assess their effectiveness in diagnosing a bearing defect in a gearbox, least mean square (LMS), linear prediction, spectral kurtosis and fast block LMS. These algorithms were applied to decompose the measured vibration signal into deterministic and random parts with the latter containing the bearing signal. These techniques were applied to identify a bearing fault in a gearbox employed for an aircraft control system for which endurance tests were performed. The results show that the LMS algorithm is capable of detecting the bearing fault earlier in comparison with the other algorithms.

230. ELASHA, F., RUIZ-CÁRCEL, C. & MBA, D.: "Detection of machine soft foot by vibration analysis", *Insight – Non-Destructive Testing and Condition Monitoring, BINDT*, *vol. 56*, *issue. 11*, pp. 622-626, DOI: 10.1784/insi.2014.56.11.622, 2014
Soft foot is considered to be one of the main causes of vibration problems in rotating machinery. However, there have been relatively limited research efforts to develop robust diagnosis tools for the early detection of such problems, particularly in scenarios where the operational vibration background noise of the machine is high. All previous studies have utilised the Fourier spectrum to diagnose soft foot symptoms. The present study is aimed at developing a series of signal processing techniques to reduce the effect of vibration background noise whilst extracting the fault feature. Three signal processing techniques were applied: adaptive filter, spectral kurtosis and envelope analysis. All three techniques were applied to measured vibration signals acquired from a motor-compressor test-rig. In conclusion, it is shown that the techniques detected motor soft foot more effectively than the conventional spectral method.

231. ELASHA, F., RUIZ-CÁRCEL, C., & MBA, D.: "Effectiveness of adaptive filter algorithms and spectral kurtosis in bearing faults detection in a gearbox", *International Conference on Vibration Engineering and Technology of Machinery, Manchester, United Kingdom*, *vol. 23*, pp. 219-229, DOI: 10.1007/978-3-319-09918-7_19, 9-11 Sep 2014
Bearing faults detection at the earliest stages is vital in avoiding future catastrophic failures. Many traditional techniques have been established and utilized in detecting bearing faults, though, these diagnostic techniques are not always successful when the bearing faults take place in gearboxes where the vibration signal is complex; under such circumstances it may be necessary to separate the bearing signal from the complex signal. The objective of this paper is to assess the effectiveness of an adaptive filter algorithms compared to a Spectral Kurtosis (SK) algorithm in diagnosing a bearing defects in a gearbox. Two adaptive filters have been used for the purpose of bearing signal separation, these algorithms were Least Mean Square (LMS) and Fast Block LMS (FBLMS) algorithms. These algorithms were applied to identify a bearing defects in a gearbox employed for an aircraft control system for which endurance tests were performed. The results show that the LMS algorithm is capable of detecting the bearing fault earlier in comparison to the other algorithms.

232. ELASHA, F., RUIZ-CÁRCEL, C., MBA, D., KIAT, G., NZE, I. & YEBRA, G.: "Pitting detection in worm gearboxes with vibration analysis", *Engineering Failure Analysis*, *vol. 42*, pp. 366-376, DOI: 10.1016/j.engfailanal.2014.04.028, 2014
Diagnostics of worm gear defects with vibration analysis is challenging and this is reflected in the limited number of publications. However, these gears are commonly used in many applications such as escalators, mills, and conveyors, and significant cost may arise from their down time due to unidentified defects. This paper aims to apply various vibration analysis techniques to diagnose the presence of naturally developed faults within worm

gearboxes. The condition of three different worm gearboxes were assessed using various vibration signal analysis techniques including a few statistical measures, Spectral Kurtosis and enveloping. This was undertaken in an attempt to identify the presence of defects within the worm gearboxes. It is shown that irrespective of the predominantly sliding motion of the gears, diagnosis of faults is feasible as long as the appropriate analysis technique is employed. In addition the results show sensitivity to the direction of vibration measurement.

233. ELASHA, F., TEIXEIRA, J.A. & MBA, D.: "Failure prediction of tidal turbine gearboxes", *The 3rd International Workshop and Congress on eMaintenance, Luleå University of Technology, Sweden*, pp. 49-54, DOI: 10.13140/RG.2.1.1080.4563, 17-18 June 2014
In order to truly minimize the maintenance cost and prevent failures of tidal turbine gearboxes, there exists a fundamental need for a prognostic tool that can reliably estimate the current health and reasonably predict the future condition of the gearbox. The research presented is aimed at developing a prognostic tool to predict the remaining life of the gearbox during operation and utilise this tool for maintenance planning. A prognostic model for the remaining life prediction of a gearbox has been developed.This model utilises the data collected by a monitoring system to predict the future condition of the gearbox. The result showed that applying real load condition results in reduction of time to failure initiation compared to average condition.

234. ELASHA, F., TOGNERI, M., MBA, D. & TEIXEIRA, J.A.: "Life Prediction of Tidal turbine Gearboxes", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Premature gearbox failures have plagued the wind turbine industry, and considerable research efforts continue to address this challenge, tidal turbine gearboxes are expected to experience higher mechanical failure rates given they will experience higher torque and thrust forces. In order to minimize the maintenance cost and prevent unexpected failures there exists a fundamental need for prognostic tools that can reliably estimate the current health and predict the future condition of the gearbox. This paper presents a life assessment methodology for tidal turbine gearboxes which was developed with synthetic data generated using a blade element momentum theory (BEMT) model. The latter has been used extensively for performance and load modelling of tidal turbine.

235. EVANS, P., MASON-JONES, A., WOOLDRIDGE, C., WILSON, C., O'DOHERTY, D.M. & O'DOHERTY, T.: "Constraints on extractable power from energetic tidal straits", *Renewable Energy*, *vol. 81*, pp. 707-722, DOI: 10.1016/j.renene.2015.03.085, 2015
National efforts to reduce energy dependency on fossil fuels have prompted examination of macrotidal nearshore sites around the United Kingdom (UK) for potential tidal stream resource development. A number of prospective tidal energy sites have been identified, but the local hydrodynamics of these sites are often poorly understood. Tidal energy developers rely on detailed characterisation of tidal energy sites prior to device installation and field trials. Although first-order appraisals may make macrotidal tidal straits appear attractive for development, detailed, site-specific hydrodynamic and bathymetric surveys are important for determining site suitability for tidal stream turbine (TST) installation. Understanding the ways in which coastal features affect tidal velocities at potential TST development sites will improve identification and analysis of physical constraints on tidal energy development. This paper presents and examines tidal velocity data measured in Ramsey Sound (Pembrokeshire, Wales, UK), an energetic macrotidal strait, which will soon host Wales' first TST demonstration project. While maximum tidal velocities in the strait during peak spring flood exceed 3 m s-1, the northern portion of Ramsey Sound exhibits a marked flood-dominated tidal asymmetry. Furthermore, local bathymetric features affect flow fields that are spatially heterogeneous in three dimensions, patterns that depth-averaged velocity data (measured and modelled) tend to mask. Depth-averaging can therefore have a significant effect on power estimations. Analysis of physical and hydrodynamic characteristics in Ramsey Sound, including tidal velocities across the swept area of the pilot TST, variations in the stream flow with depth, estimated power output, water depth and bed slope, suggests that the spatial and temporal variability in the flow field may render much of Ramsey Sound unsuitable for tidal power extraction. Although the resource potential depends on velocity and bathymetric conditions that are fundamentally local, many prospective tidal energy sites are subject to similar physical and hydrodynamic constraints. Results of this study can help inform site selection in these complicated, highly dynamic macrotidal environments. In order to fully characterise the structure of the tidal currents, these data should be supplemented with 3-D modelling, particularly in areas subject to a highly irregular bathymetry and complicated tidal regime.

236. EVANS, P.S., LAZARUS, E., MASON-JONES, A., O'DOHERTY, D.M. & O'DOHERTY, T.: "Wake Characteristics of a Natural Submerged Pinnacle and Implications for Tidal Stream Turbine Installations", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Measurements of tidal velocities in the vicinity of natural submerged features are rare given the cost and difficulties of collecting data in these hostile environments. This has pushed much of the research to laboratory and numerical modelling studies. However, understanding how these natural features affect flow fields has important implications for tidal stream turbine (TST) deployment, particularly those pertaining to tidal turbine

arrays; siting TSTs too close to one another affects their performance and creates undesirable structural loadings. This paper quantifies the wake characteristics of a submerged pinnacle in a macrotidal strait, using Ramsey Sound, Wales, UK as a field site. Vessel-mounted ADCP surveys were undertaken as a set of three transects downstream of this natural pinnacle during the flood tide to examine the streamwise and cross-channel wake extents. The results of this research suggest that wake recovery of submerged pinnacles is controlled by both velocity magnitude in the principal flow direction and the local bathymetry. The latter has a more significant effect on wake migration from the centreline, which is an important consideration when designing array configurations.

237. FAIRLEY, I.A., MASTERS, I. & KARUNARATHNA, H.: “Numerical modelling of Storm and Surge Events on Offshore Sandbanks” *Marine Geology, vol. 371,* pp 106-119, doi:10.1016/j.margeo.2015.11.007, 2016
This contribution uses a 3 dimensional coastal area numerical model, DHI's MIKE3, to simulate the impact of storm and surge events on offshore sandbanks. Three offshore sandbanks in the Bristol Channel are considered due to the region's sensitivity to anthropogenic pressures and the gradients in wave and tidal forcing in the area. Two extreme storm and surge events are simulated: one co-incident with spring tide and the other with neap tide. Reference simulations of astronomical tidal forcing only are also presented. It is shown that for the two sandbanks with greater wave exposure, storm conditions can provide a mechanism for the maintenance of crest position. For these cases, bed level changes over the crest are in the opposite direction compared to astronomically forced change. For the least wave exposed bank, both wave and tide only cases exhibit similar patterns of bed level change. Volumetric changes under astronomical forcing are shown to vary with changing maximum tidal current. Accretion occurs over a neap tidal cycle for all three sandbanks and as maximum tidal current increases the amount of accretion increases; however, over a spring tidal cycle accretion is observed for the less tidally dominated site but increasing maximum tidal current leads to reduced accretion and then erosion for the most tidally dominated bank. Volumetric changes under storm conditions are related to sandbank morphology and setting rather than relative wave exposure. The two single banks closely tied to headlands show similar magnitude of percentage volumetric change despite being at the two extremes of wave exposure and greater erosion occurs over the neap tide event. The sandbank that has associated secondary banks shows lesser percentage change and greater erosion over the spring tide event.

238. FERNANDEZ-RODRIGUEZ, E., STALLARD, T.J. & STANSBY, P.K.: "Experimental study of extreme thrust on a tidal stream rotor due to turbulent flow and with opposing waves", *Journal of Fluids and Structures*, *vol. 51*, pp. P354-361, DOI: 10.1016/j.jfluidstructs.2014.09.012, 2014
Time-varying thrust has been measured on a rotor in shallow turbulent flow at laboratory scale. The onset flow has a turbulence intensity of 12% at mid depth and a longitudinal turbulence length scale of half the depth, about 5 times the vertical scale, typical of shallow flows. The rotor is designed to have thrust and power coefficient variations with tip speed ratio close to that of a full-scale turbine. Three extreme probability distributions give similar thrust exceedance values with the Type 1 Pareto in mid range which gives 1:100, 1:1000 and 1:10 000 exceedance thrust forces of 1.38, 1.5 and 1.59 times the mean value. With opposing waves superimposed the extreme thrust distribution has a very similar distribution to the turbulent flow only. Exceedance forces are predicted by superposition of a drag force with drag coefficient of 2.0 based on the wave particle velocity only and with an unchanged mean thrust coefficient of 0.89. These values are relevant for the design of support structures for marine turbines.

239. FOLLEY, M. & WHITTAKER, T.: "Validating a spectral-domain model of an OWC using physical model data", *International Journal of Marine Energy*, *vol. 2*, pp. 1-11, DOI: 10.1016/j.ijome.2013.05.003, Jun-13
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 terms 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 using the orifice pressure/flow characteristics and a single calibration sea-state respectively. 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-domain model’s prediction of power capture is typically less than 5%. 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.

240. FROST, C.H., EVANS, P.S, MORRIS, C.E., MASON-JONES, A., O’DOHERTY, D.M. & O’DOHERTY,T.: "Flow Misalignment and Tidal Stream Turbines", *EWTEC conference, Nantes, France*, DOI: 10.13140/RG.2.1.3544.7761, 7-10 Sep 2015

Extensive Research and Development (R&D) within the tidal energy industry is pushing this sector towards commercial viability, with full scale prototypes starting to meet the challenges of the marine environment. This paper combines velocity data collected from Ramsey Sound (Pembrokeshire, Wales), with Computational Fluid Dynamics (CFD) to assess the impact of non-rectilinear flows on turbine rotor performance. This requires both the geometry of the turbine and the surrounding free stream velocity to be studied. From the site data, the majority of the velocities tend to fall within a ±20° misalignment to the principle flow direction for velocities greater than the economic viable threshold of 2 ms-1. From the CFD it was found that the non-dimensional performance parameters reduced with increasing angles of misalignment between the axis of rotation and free stream velocity. The resultant magnitude of the bending moments about the head of the driveshaft for the misaligned turbines were found to be up to nine times greater, than the aligned turbine. The paper shows that the tolerance to axial flow misalignment between the free stream velocity and axis of rotation of a turbine requires defining, in order to avoid the detrimental effects it has on performance and loading.

241. FROST, C.H., MORRIS, C.E., MASON-JONES, A., O'DOHERTY, D.M. & O'DOHERTY,T.: "Effects of tidal directionality on tidal turbine characteristics", *Renewable Energy*, *vol. 78*, pp. 609-620, DOI: 10.1016/j.renene.2015.01.053, 2015
With many Tidal Energy Conversion (TEC) devices at full scale prototype stage there are two distinct design groups for Horizontal Axis Tidal Turbines (HATTs). Devices with a yaw mechanism allowing the turbine to always face into the flow, and devices with blades that can rotate through 180° to harness a strongly bi-directional flow. As marine turbine technology verges on the realm of economic viability this paper reveals the performance of Cardiff University's concept tidal turbine with its support structure either upstream or downstream and with various proximities between the rotating plane of the turbine and its support stanchion. Through the use of validated Computational Fluid Dynamics (CFD) modelling this work shows the optimal proximity between rotor plane and stanchion as well as establishing, in the given context, the use of a yaw mechanism to be superior to a bi-directional system from a performance perspective.

242. GREENWOOD, C.E., VENUGOPAL, V., CHRISTIE, D., MORRISON, J. & VÖGLER, A.: "Wave modelling for potential wave energy sites around the Outer Hebrides", *32th International Conference on Ocean, Offshore and Arctic Engineering OMAE2013, Nantes France*, DOI: 10.1115/OMAE2013-11356, 9-14 June 2013
This paper presents the results of a numerical wave modelling study carried out to assess the near shore wave energy resource around potential wave energy sites at the Outer Hebrides in the United Kingdom. This study uses Danish Hydraulic Institute's MIKE 21 Spectral Wave model suite. Input boundary conditions are obtained from a Datawell directional wave buoy located approximately 16 km off the coast of Lewis in 60 metre depth. Additional data collected from a submerged Acoustic Wave and Current profiler (AWAC) located at 13 metre depth offshore at one of the wave energy development sites was used to calibrate and validate the wave model for separate time periods. The calibration process allows the manipulation of white capping, bottom friction and wave breaking parameters to alter the energy dissipation across the model domain. The altered parameters gave a significantly better agreement between modelled and measured results than the model defaults. While the average wave conditions provided a relatively straightforward calibration process the more extreme storm events significantly under predicted the wave height. After several trials in altering model coefficients a good agreement was reached between the model results and the AWAC data. These new sets of calibration parameters enable the simulation of wave heights within 13% for the AWAC data and marginally more for wave periods for the first 6 months of 2012.

243. GROSVENOR, R.I., ALLMARK, M. & PRICKETT, P.W.: "Performance and Condition Monitoring of Tidal Stream Turbines", *2nd Eur. Conf. of the Prognostics and Health Management Soc., Nantes, France*, 8-10 July 2014
Research within the Cardiff Marine Energy Research Grou (CMERG) has considered the integrated mathematical modelling of Tidal Stream Turbines (TST). The modelling studies are briefly reviewed. This paper concentrates on the experimental validation testing of small TST models in a water flume facility. The dataset of results, and in particular the measured axial thrust signals are analysed via timefrequency methods. For the 0.5 m diameter TST the recorded angular velocity typically varies by ± 2.5% during the 90 second test durations. Modelling results confirm the expectations for the thrust signal spectrums, for both optimum and deliberately offset blade results. A discussion of the need to consider operating conditions, condition monitoring sub-system refinements and the direction of prognostic methods development, is provided.

244. GROSVENOR, R.I., PRICKETT, P.W., ALLMARK, M. & FROST, C.H.: "The monitoring and validation of scale model tidal stream turbines", *COMADEM 2014, Brisbane, Australia*, 16-Sep-14
The Cardiff Marine Energy Research Group (CMERG) has established a series of generic design guidelines for the developing commercial deployment of tidal stream turbines (TST). This paper briefly reviews the contributions of the mathematical modelling studies to this field. The mathematical models are validated via testing at a water flume facility at Liverpool University. This testing also evaluated condition and performance monitoring techniques. A dataset of results was utilized for these aspects and the ensuing monitoring analyses form the focus

of this paper. The results are for both ‘optimum’ and ‘offset’ setups. The approach aims to extract any rotational effects from the small cyclic variations observed in the axial thrust signals. The potential for using the results obtained as part of a condition monitoring regime is discussed, along with anticipated refinements. The paper concludes with a brief description of the next generation of scale model TST that is about to be deployed for further testing.

245. GU, H.B., QIAN, L., CAUSON, D.M. MINGHAM, C.G. & LIN, P.: "Numerical Simulation of Water Impact of Solid Bodies with Vertical and Oblique Entries", *Ocean Engineering*, *vol. 75*, pp. P128-137, DOI: 10.1016/j.oceaneng.2013.11.021, 01-Jan-14
The flow problem of hydrodynamic impact during water entry of solid objects of various shapes and configurations is simulated by a two-fluid free surface code based on the solution of the Navier–Stokes equations (NSE) on a fixed Cartesian grid. In the numerical model the free surface is captured by the level set function, and the partial cell method combined with a local relative velocity approach is applied to the simulation of moving bodies. The code is firstly validated using experimental data and other numerical results in terms of the impact forces and surface pressure distributions for the vertical entry of a semi-circular cylinder and a symmetric wedge. Then configurations of oblique water entry of a wedge are simulated and the predicted free surface profiles during impact are compared with experimental results showing a good agreement. Finally, a series of tests involving vertical and oblique water entry of wedges with different heel angles are simulated and the results compared with published numerical results. It is found that the surface pressure distributions and forces predicted by the present model generally agree very well with other numerical results based on the potential flow theory. However, as the current model is based on the solution of the NSE, it is more robust and can therefore predict, for example, the formation and separation of the thin flow jets (spray) from surface of the wedge and associated ventilation phenomena for the cases of oblique water entry when the horizontal velocity is dominant. It is also noted that the potential flow theory can result in over-estimated negative pressures at the tip of the wedge due to its inherent restriction to nonseparated flows.

246. HARDING, S. & BRYDEN, I.G.: "Directionality in prospective Northern UK tidal current energy deployment sites", *Renewable Energy*, *vol. 44*, pp. 474-477, DOI: 10.1016/j.renene.2012.02.003, Aug-12
The directionality of the tidal flow throughout the tidal cycle has important implications for tidal energy capture with respect to turbine performance, capacity factor, and structural loading. There has been a tendency to infer that energetic sites possess near bi-directional flows or that there are sufficient sites with near bi-directional flows such that more omni-directional flow tidal currents can be neglected. This technical note investigates the connection between directionality and the incident kinetic energy density of tidal currents in the Northern United Kingdom. It demonstrates a positive correlation between these flow parameters and quantifies this through the analysis of real tidal velocity data.

247. HARNOIS, V., JOHANNING, L. & THIES, P.R.: "Wave Conditions Inducing Extreme Mooring Loads on a Dynamically Responding Moored Structure.", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
The aim of this paper is to determine which wave conditions are inducing extreme mooring loads on a highly dynamically responding moored structure. Currently, the design of a mooring system for a typical oil and gas offshore structure is based on the prediction of the extreme mooring loads for a limited number of wave conditions along the envelope of a wave scatter diagram. During the design process, an inappropriate choice of wave conditions could lead to an incorrect estimation of extreme mooring loads, which may result either in the loss of the mooring system or in a costly overdesign. This paper draws on mooring tensions and wave conditions that have been recorded at a mooring test facility using a multi-leg catenary mooring system. The mooring loads have been assessed to identify extreme mooring loads, which have been analysed in respect to the corresponding wave conditions. Further, joint probability distributions of wave conditions that results in extreme mooring loads have been determined. The most important finding is that extreme mooring loads were not necessarily identified to occur on the envelope of the wave climate parameter scatter diagram.

248. HASHEMI, M.R., NEILL S.P. & DAVIES, A.G.: "A numerical study of wave and current fields around Ramsey Island - tidal energy resource assessment", *XIXth TELEMAC-MASCARET User Conference, Oxford, United Kingdom*, Oct-12
In the Irish Sea, the best marine renewable energy sites are subjected to strong currents and exposed to relatively large waves (e.g. around Ramsey island and in the Bristol Channel). The objective of this research is to present the potential of the TELEMAC modelling system in various aspects of marine renewable energy studies such as multi-scale modelling, and wave-tide interaction. Firstly, an idealised triangular domain was modelled to study the impact of tides on quantifying the wave power resource. The overall dimensions of this case study resemble those of the Bristol Channel. The results of the idealised case study demonstrate that ignoring the tides when estimating wave power generates considerable errors, since wave power is related to significant wave height squared. Next, a multi-scale unstructured mesh model of the Irish Sea was developed using TELEMAC. Spatial and temporal

variations of the currents around Ramsey Sound were captured using a relatively fine mesh (~40m). Despite the strong current field and complex bathymetry of this region, the multi-scale tidal model led to convincing results. Some recommendations for research and priorities for data collection have been identified.

249. HASHEMI, M.R., NEILL, S.P. & DAVIES, A.G.: "A coupled tide-wave model for the NW European shelf seas", *Geophysical & Astrophysical Fluid Dynamics*, *vol. 109*, *issue. 3*, DOI: 10.1080/ 03091929.2014.944909, 14-Aug-14
Understanding the interaction of tides and waves is essential in many studies, including marine renewable energy, sediment transport, long-term seabed morphodynamics, storm surges and the impacts of climate change. In the present research, a COAWST model of the NW European shelf seas has been developed and applied to a number of physical processes. Although many aspects of wave–current interaction can be investigated by this model, our focus is on the interaction of barotropic tides and waves at shelf scale. While the COWAST model was about five times more computationally expensive than running decoupled ROMS (ocean model) and SWAN (wave model), it provided an integrated modelling system which could incorporate many wave–tide interaction processes, and produce the tide and wave parameters in a unified file system with a convenient post-processing capacity. Some applications of the model such as the effect of tides on quantifying the wave energy resource, which exceeded 10% in parts of the region, and the effect of waves on the calculation of the bottom stress, which was dominant in parts of the North Sea and Scotland, during an energetic wave period are presented, and some challenges are discussed. It was also shown that the model performance in the prediction of the wave parameters can improve by 25% in some places where the wave-tide interaction is significant.

250. HASHEMI, M.R., NEILL, S.P., ROBINS, P.E., DAVIES, A.G. & LEWIS, M.J.: "Effect of waves on the tidal energy resource at a planned tidal stream array", *Renewable Energy*, *vol. 75*, pp. 626-639, DOI: 10.1016/j.renene.2014.10.029, Mar-15
Wave–current interaction (WCI) processes can potentially alter tidal currents, and consequently affect the tidal stream resource at wave exposed sites. In this research, a high resolution coupled wave-tide model of a proposed tidal stream array has been developed. We investigated the effect of WCI processes on the tidal resource of the site for typical dominant wave scenarios of the region. We have implemented a simplified method to include the effect of waves on bottom friction. The results show that as a consequence of the combined effects of the wave radiation stresses and enhanced bottom friction, the tidal energy resource can be reduced by up to 20% and 15%, for extreme and mean winter wave scenarios, respectively. Whilst this study assessed the impact for a site relatively exposed to waves, the magnitude of this effect is variable depending on the wave climate of a region, and is expected to be different, particularly, in sites which are more exposed to waves. Such effects can be investigated in detail in future studies using a similar procedure to that presented here. It was also shown that the wind generated currents due to wind shear stress can alter the distribution of this effect.

251. HENRIQUES, T.A.J, HEDGES, T.S., OWEN, I. & POOLE, R.J.: "The effect of wave-current interaction on the near-wake of horizontal axis tidal stream turbines", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
This paper describes an experimental study of the near-wake characteristics of a scale-model horizontal axis tidal stream turbine operating under an inititally uniform steady current upon which surface waves were imposed. The experiments were carried out in a recirculating water channel using a three-bladed model turbine with a diameter of 0.5m under flow conditions independent of Reynolds number. A wavemaker was installed at the inlet to the channels working section in order to create regular surface waves travelling in the same direction as the current. An intermediate depth wave with a height of 82mm and a period of 0.74s, resulting in a wavelength of 2m, was imposed on a current with a mean velocity of 0.9m/s. Both the wave profile and water kinematics were measured directly and showed excellent agreement with Stokes' second-order wave theory. The wave-current interaction induced strong fluctuations in both power output and thrust on the turbine but without significantly affecting the mean values. Furthermore, the wave-induced velocities were seen to enhance the mixing between the turbine wake and the main flow, so increasing the downstream velocity recovery and shortening the wake. This may, in turn, reduce the distance required between devices in farms exposed to significant background wave activity, thus potentially increasing the power extracted from tidal stream farms.

252. HENRY, A., ABADIE, T., NICHOLSON, J., MCKINLEY, A., KIMMOUN, O., & DIAS, F.: "The Vertical Distribution and Evolution of Slam Pressure on an Oscillating Wave Surge Converter", *. International Conference on Ocean, Offshore and Arctic Engineering, St. John's, Canada*, 31 May - 5 June 2015
The accurate definition of the extreme wave loads which act on offshore structures represents a significant challenge for design engineers and even with decades of empirical data to base designs upon there are still failures attributed to wave loading. The environmental conditions which cause these loads are infrequent and highly non-linear which means that they are not well understood or simple to describe. If the structure is large enough to affect the incident wave significantly further non-linear effects can influence the loading. Moreover if the structure is floating and excited by the wave field then its responses, which are also likely to be highly non-linear, must be

included in the analysis. This makes the description of the loading on such a structure difficult to determine and the design codes will often suggest employing various tools including small scale experiments, numerical and analytical methods, as well as empirical data if available. Wave Energy Converters (WECs) are a new class of offshore structure which pose new design challenges, lacking the design codes and empirical data found in other industries. These machines are located in highly exposed and energetic sites, designed to be excited by the waves and will be expected to withstand extreme conditions over their 25 year design life. One such WEC is being developed by Aquamarine Power Ltd and is called Oyster. Oyster is a buoyant flap which is hinged close to the seabed, in water depths of 10 to 15m, piercing the water surface. The flap is driven back and forth by the action of the waves and this mechanical energy is then converted to electricity. It has been identified in previous experiments that Oyster is not only subject to wave impacts but it occasionally slams into the water surface with high angular velocity. This slamming effect has been identified as an extreme load case and work is ongoing to describe it in terms of the pressure exerted on the outer skin and the transfer of this short duration impulsive load through various parts of the structure. This paper describes a series of 40th scale experiments undertaken to investigate the pressure on the face of the flap during the slamming event. A vertical array of pressure sensors are used to measure the pressure exerted on the flap. Characteristics of the slam pressure such as the rise time, magnitude, spatial distribution and temporal evolution are revealed. Similarities are drawn between this slamming phenomenon and the classical water entry problems, such as ship hull slamming. With this similitude identified, common analytical tools are used to predict the slam pressure which is compared to that measured in the experiment.

253. HU, Z.Z, MAI, T., GREAVES, D. & RABY, A.: "A numerical and experimental study of a simplified FPSO in extreme free surface waves using OpenFOAM", *27th ISOPE conference. Rhodes, Greece*, 2016
The aim of the present paper is to investigate the detailed characteristics of wave impacts on a rigid truncated vertical wall, numerical data are compared with experiment for the impact pressures and surface elevation. The characterisics of the impacts are found to depend on the breaker conditions and different types of impact are identified and discussed. Accurate prediction of the most severe wave loading is crucial to the design of many types of coastal structure and the laboratory studies have demonstrated impacts similar to those referenced by Bullock et al. 2007. In this paper, we use the open source Computational Fluid Dynamics (CFD) package-Open Field Operation and Manipulation (OpenFOAM) as a numerical wave tank (NWT) to study the numerical simulation of nonlinear wave impact on a vertical wall. The wave boundary condition is based on NewWave for representation of the extreme wave event together with second-order Stokes wave theory, as described by Dalzell (1999) and Hu et al. (2014) and is imposed as the inlet boundary condition in a Numerical Wave Tank (NWT). A fixed rigid vertical wall is placed at a location in the NWT, where it will undergo severe wave impact. A Volume of Fluid (VoF) interface capturing approach is used to model the free surface. The incompressible Navier-Stokes equations are solved using a finite volume method on unstructured meshes. The Nonlinear k-ϵ model is selected for this study because the turbulence model becomes important in cases of wave breaking as considered in the present work.

254. HU, Z.Z, MAI, T., GREAVES, D. & RABY, A.: "Hydroelastic Investigation of Extreme Wave Impact on a Truncated Vertical Wall", *7th international Conference on Hydroelasticity in marine Technology, Split, Croatia*, pp. 55-64, 2015
This paper describes an investigation of hydroelastic wave impact of a NewWave (see Tromans et al. (1991)) impacting on an elastically supported wall. The experimental study was carried out in a wave flume at the COAST laboratory at Plymouth University. The truncated vertical wall is a rigid aluminium plate of 0.56 m width by 0.6 m height and is 0.012 m thick (Plate 1 in Figure 1), connected to a rigid wall by four springs. The numerical simulation is based on the open source Computational Fluid Dynamics (CFD) package Open Field Operation and Manipulation (OpenFOAM®). It has been extended with a new boundary condition for extreme wave generation in the waves2Foam library, in which either first or second-order Stokes wave theory can be imposed as the inlet boundary condition in a Numerical Wave Tank (NWT). A DFBI (Dynamic Fluid Body Interaction) model is used to simulate the linear spring coupling system (see Figure 2), which has the basic form of a mass-spring-dashpot system for the truncated vertical wall in the NWT (see Figure 3). The turbulence model becomes important in the case of wave breaking and the k -ϵ turbulence model is used in the present work. Impact pressures, wave runup, total forces and wall displacement will be presented and comparison between the numerical simulation and experiments made.

255. HU, Z.Z., GREAVES, D. & RABY, A.: "Numerical simulation of extreme wave impact on a rigid truncated vertical wall using OpenFOAM", *Partnership for Research in Marin Reneable Energy (PRIMARE) 2nd Annual conference. Exeter, U.K*, 2015
In this paper, we use the open source Computational Fluid Dynamics (CFD) package-Open Field Operation and Manipulation (OpenFOAM) as a numerical wave tank (NWT) to study highly nonlinear extreme free surface flows. The extreme wave formulation prescribed as an inlet condition is due to [1] and [2], which is based on a second

order stokes focused wave. The incompressible Unsteady Reynolds-averaged Navier-Stokes Equations (URANSE) are solved using a finite volume method on unstructured meshes. A Volume of Fluid (VoF) interface capturing approach is used to model the free surface. Extreme wave boundary conditions are prescribed at the inlet of the NWT and extreme waves acting on a simplified Floating Production Storage and Offloading (FPSO) platform responding with Six Degrees of Freedom (6DoF) motion are simulated. The physical model experiments are carried out in Plymouth University's COAST Laboratory ocean basin and comparison of the wave run up, force, pressure and motions are drawn between the experiment and the OpenFOAM results. The numerical results show that OpenFoam is a suitable tool for simulating large offshore structures under extreme wave loading and can be used to predict extreme wave interactions as it is able to solve two-phase flow in 3D domains.

256. JOHNSTONE, C., MCCOMBES, T., BAHAJ, A.S., MYERS, L., HOLMES, B., KOFOED, J.-P., & BITTENCOURT, C.: "EquiMar: Development of Best Practices for the Engineering Performance Appraisal of Wave and Tidal Energy Converters", *EWTEC 2011, Southampton, UK*, Sep-11
At the present time there are no approved standards or recognised best practices being implemented for the performance appraisal and benchmarking of wave and tidal energy converters. As such, this develops considerable misunderstanding between device developers, testing centres, investors/ financiers etc when attempting to quantify the performance of a device since it makes it very difficult to reference and benchmark the performance of a marine energy converter. The EC Framework Programme VII EquiMar project has set out to develop a suite of Best Practices to be adopted when undertaking the performance evaluation of such systems in order to address this deficiency. This paper reports the development of a set of 'Best Practices' within the ECFPVII EquiMar project to be adopted for the performance quantification of wave and tidal energy converters as they evolve from an engineering concept to commercial scale deployment.

257. JONES, D.K., ZOU, Q. & REEVE, D.E.: "Simulation of wave overtopping with storm surge using a RANS-VOF model", *Journal of Flood Risk Management*, *vol. 6*, *issue. 2*, 2012
In this paper, we investigate the process of embankment wave overtopping combined with overflow because of extreme surge levels that are above the embankment crest. A Reynolds-averaged Navier-Stokes volume of fluid (RANS-VOF) model is employed to simulate the hydrodynamics. To investigate the success of the model at reproducing the hydrodynamic processes, the model is compared with experimental laboratory measurements. Comparisons are performed for quantities including discharge, depth and velocity. The overtopping discharge predicted by the model is compared against empirical design methods. Specific conditions under which discrepancies occur between the mode, laboratory measurements and design formulae are identified and explained and design guidance is provided. This study has demonstrated that the RANS model can adequately represent the complex hydrodynamics encountered in extreme storms where combined overflow and wave overtopping occurs. A tendency was found for the model to somewhat over-predict the overtopping volume as wave heights increase and has been hypothesised as being due to shortcomings of the representation of turbulence within the model.

258. KURNIAWAN, A., CHAPLIN, J., GREAVES, D., HANN, M., & FARLEY, F.: "Wave energy absorption by a floating air bag", *Journal of Fluid Mechanics*, 2016
A floating air bag, ballasted in water, expands and contracts as it heaves under wave action. Connecting the bag to a secondary volume via a turbine transforms the bag into a device capable of generating useful energy from the waves. Small-scale measurements of the device reveal some interesting properties, which are successfully predicted numerically. Owing to its compressibility, the device can have a resonance period longer than that of a rigid device of the same shape and size, without any phase control. Furthermore, varying the amount of air in the bag is found to change its shape and hence its dynamic response, while varying the turbine damping or the air volume ratio changes the dynamic response without changing the shape.

259. LAMONT-KANE, P., MCKINLEY, A., HENRY, A., NICHOLSON, J., FOLLEY, M., & ELSAESSER, B.: "Investigating Extreme Loads on an Oscillating Wave Surge Converter", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
A major difficulty in the design of full scale Wave Energy Converters is the need to design for two conflicting design criteria. In one instance devices must be designed to couple heavily to the incident wave force resulting in the efficient extraction of energy in small sea states, however devices must also be capable of withstanding the harsh conditions encountered during extreme seas. This paper presents an initial investigation of the extreme wave loading of a generic, surface-piercing, pitching flap-type device deployed in near shore wave conditions. Slamming of the flap is selected as the extreme load event for further investigation and the experimental methodologies employed are described. Preliminary results showing both local and global loading under such events are presented for the case of a flap tested in a 3-dimensional environment. Results are presented which show flap slamming effects on the pressures experienced on the front face of the flap.

260. LEWIS, M.J., NEILL, S.P. & ELLIOTT, A.J.: "Inter-annual variability of two contrasting offshore sand banks in a region of extreme tidal range", *Journal of Coastal Research*, *vol. 31*, pp. 265-275, DOI: 10.2112/JCOASTRES-D-14-00010.1, 2015
Offshore sand banks play important roles for coastal flood protection and fisheries, and they are sources of marine aggregates. An 11-year record (1991–2002) of annual bathymetric surveys from two sand banks (Nash and Helwick) in the Bristol Channel (U.K.) were analysed. Both sand banks have a history of commercial dredging, and have dimensions of the order 10 km by 1 km, with a crest height rising to around 20–25 m above the surrounding sea bed. The crest at Nash Bank is exposed on the lowest spring tides, while Helwick Bank is always covered to a depth of at least 3 m. The volume of Nash Bank decreased over 10 years, and dredging was estimated to be responsible for around one third of this reduction. The volume of Helwick Bank also decreased over an 8-year period, but at a rate six times greater than the loss due to dredging. Significant interannual variability of sand bank morphology was calculated at both sites. The time during which waves alone could induce sediment transport over the sand banks was calculated between each survey date (the effective wave climate). The change in sand bank volume correlated well to the effective wave climate: a linear regression score of 77% (-0.88 Pearson correlation at the 95% significance level) and 69% (0.83 Pearson correlation at the 95% significance level) were found at Helwick and Nash, respectively. A one-dimensional morphodynamic model (UNIBEST-TC), simulated storm wave–induced changes to sand bank morphology that were consistent with those observed. Therefore, the interannual variability within storm wave events could be responsible for the observed natural variability of sand bank volume and morphology observed at both sites. We conclude that it is important to understand anthropogenic impacts upon sand banks within the context of natural variability.

261. LEWIS, M.J., NEILL, S.P., ROBINS, P.E. & HASHEMI, M.R.: "Resource assessment for future generations of tidal-stream energy arrays", *Energy*, *vol. 83*, pp. 403-415, DOI: 10.1016/j.energy.2015.02.038, 2015
Tidal-stream energy devices currently require spring tide velocities (SV) in excess of 2.5 m/s and water depths in the range 25–50 m. The tidal-stream energy resource of the Irish Sea, a key strategic region for development, was analysed using a 3D hydrodynamic model assuming existing, and potential future technology. Three computational grid resolutions and two boundary forcing products were used within model configuration, each being extensively validated. A limited resource (annual mean of 4 TJ within a 90 km2 extent) was calculated assuming current turbine technology, with limited scope for long-term sustainability of the industry. Analysis revealed that the resource could increase seven fold if technology were developed to efficiently harvest tidal-streams 20% lower than currently required (SV > 2 m/s) and be deployed in any water depths greater than 25 m. Moreover, there is considerable misalignment between the flood and ebb current directions, which may reduce the practical resource. An average error within the assumption of rectilinear flow was calculated to be 20°, but this error reduced to ~3° if lower velocity or deeper water sites were included. We found resource estimation is sensitive to hydrodynamic model resolution, and finer spatial resolution (<500 m) is required for regional-scale resource assessment when considering future tidal-stream energy strategies.

262. LOPEZ, G., CONLEY, D., & GREAVES, D.: "Calibration, validation and analysis of an empirical algorithm for the retrieval of wave spectra from HF radar sea-echo", *Journal of Atmospheric and Oceanic Technology*, DOI: http://dx.doi.org/10.1175/JTECH-D-15-0159.1, 16-Dec-15
The accuracy of the wave products retrieved by a 12-MHz high-frequency (HF) phased-array radar is evaluated for a 5-month period. The two stations composing the system were deployed in 2011 to overlook the Wave Hub, a test site for marine renewable energy devices located on the southwestern coast of the United Kingdom. The system was conceived and configured to reduce the inaccuracies introduced by short time averaging and minimal overlap between stations, both associated with the most traditional HF radar deployments, whose primary activity is current measurement. Wave spectra were retrieved by an empirical algorithm distributed with Wellen Radars (WERA), which were calibrated using in situ measurements collected within the radar footprint. Evaluated through comparison against measurements acquired by three in situ devices, the results revealed estimates of significant wave height with nearly zero bias, linear correlations higher than 90%, and RMS errors that range from 29 to 44 cm. The relative error of wave energy period comparisons was within 10% for periods between 8 and 13 s, while both under- and overestimations were observed above and below that range, respectively. The validation demonstrated that when locally calibrated, the algorithm performs better than in its original form in all metrics considered. Observed discrepancies are mainly attributable to single-site estimations, antenna sidelobes, and the effect of the second-harmonic peaks of the Doppler spectrum.

263. MA, Z. H., CAUSON, D. M., QIAN, L., MINGHAM, C.G., MAI, T., GREAVES, D. & RABY, A.: "Pure and aerated water entry of a flat plate", *Phys. Fluids*, *vol. 28*, *issue. 16104*, DOI: http://dx.doi.org/10.1063/1.4940043, 2016
This paper presents an experimental and numerical investigation of the entry of a rigid square flat plate into pure and aerated water. Attention is focused on the measurement and calculation of the slamming loads on the plate. The experimental study was carried out in the ocean basin at Plymouth University's COAST laboratory. The present

numerical approach extends a two-dimensional hydro-code to compute three-dimensional hydrodynamic impact problems. The impact loads on the structure computed by the numerical model compare well with laboratory measurements. It is revealed that the impact loading consists of distinctive features including (1) shock loading with a high pressure peak, (2) fluid expansion loading associated with very low sub-atmospheric pressure close to the saturated vapour pressure, and (3) less severe secondary reloading with super-atmospheric pressure. It is also disclosed that aeration introduced into water can effectively reduce local pressures and total forces on the flat plate. The peak impact loading on the plate can be reduced by half or even more with 1.6% aeration in water. At the same time, the lifespan of shock loading is prolonged by aeration, and the variation of impulse is less sensitive to the change of aeration than the peak loading.

264. MA, Z.H., CAUSON, D.M., QIAN, L., GU, H., MINGHAM, C.G. & MARTINEZ FERRER, P.: "A GPU based compressible multiphase hydrocode for modelling violent hydrodynamic impact problems", *Computers & Fluids*, *vol. 120*, pp. 1-23, DOI: 10.1016/j.compfluid.2015.07.010, 05-Oct-15
This paper presents a GPU based compressible multiphase hydrocode for modelling violent hydrodynamic impacts under harsh conditions such as slamming and underwater explosion. An effort is made to extend a one-dimensional five-equation reduced model (Kapila et al., 2001) to compute three-dimensional hydrodynamic impact problems on modern graphics hardware. In order to deal with free-surface problems such as water waves, gravitational terms, which are initially absent from the original model, are now considered and included in the governing equations. A third-order finite volume based MUSCL scheme is applied to discretise the integral form of the governing equations. The numerical flux across a mesh cell face is estimated by means of the HLLC approximate Riemann solver. The serial CPU program is firstly parallelised on multi-core CPUs with the OpenMP programming model and then further accelerated on many-core graphics processing units (GPUs) using the CUDA C programming language. To balance memory usage, computing efficiency and accuracy on multi- and many-core processors, a mixture of single and double precision floating-point operations is implemented. The most important data like conservative flow variables are handled with double-precision dynamic arrays, whilst all the other variables/arrays like fluxes, residual and source terms are treated in single precision. Several benchmark test cases including water-air shock tubes, one-dimensional liquid cavitation tube, dam break, 2D cylindrical underwater explosion near a planar rigid wall, 3D spherical explosion in a rigid cylindrical container and water entry of a 3D rigid flat plate have been calculated using the present approach. The obtained results agree well with experiments, exact solutions and other independent numerical computations. This demonstrates the capability of the present approach to deal with not only violent free-surface impact problems but also hull cavitation associated with underwater explosions. Performance analysis reveals that the running time cost of numerical simulations is dramatically reduced by use of GPUs with much less consumption of electrical energy than on the CPU.

265. MA, Z.H., CAUSON, D.M., QIAN, L., MINGHAM, C.G., GU, H. & MARTINEZ FERRER, P.: "A Compressible Multiphase Flow Model for Violent Aerated Wave Impact Problems", *Proceedings of the Royal Society A,*, *vol. 470*, *issue. 2172*, DOI: 10.1098/rspa.2014.0542, 08-Oct-14
This paper focuses on the numerical modelling of wave impact events under air entrapment and aeration effects. The underlying flow model treats the dispersed water wave as a compressible mixture of air and water with homogeneous material properties. The corresponding mathematical equations are based on a multiphase flow model which builds on the conservation laws of mass, momentum and energy as well as the gas-phase volume fraction advection equation. A high-order finite volume scheme based on monotone upstream-centred schemes for conservation law reconstruction is used to discretize the integral form of the governing equations. The numerical flux across a mesh cell face is estimated by means of the HLLC approximate Riemann solver. A third-order total variation diminishing Runge–Kutta scheme is adopted to obtain a time-accurate solution. The present model provides an effective way to deal with the compressibility of air and water–air mixtures. Several test cases have been calculated using the present approach, including a gravity-induced liquid piston, free drop of a water column in a closed tank, water–air shock tubes, slamming of a flat plate into still pure and aerated water and a plunging wave impact at a vertical wall. The obtained results agree well with experiments, exact solutions and other numerical computations. This demonstrates the potential of the current method to tackle more general wave–air–structure interaction problems.

266. MALKI, R., WILLIAMS, A.J., CROFT, T.N., TOGNERI, M. & MASTERS, I: "A Coupled Blade Element Momentum - Computational Fluid Dynamics Model for Evaluating Tidal Stream Turbine Performance", *Applied Mathematical Modelling*, *vol. 37*, *issue. 5*, pp. 3006-3020, DOI: 10.1016/j.apm.2012.07.025, *ISSN: 0307-904X*, 2013
A modelling approach based on blade element momentum theory is developed for the prediction of tidal stream turbine performance in the ocean environment. Through the coupling of the blade element momentum method with computational fluid dynamics, the influence of upstream hydrodynamics on rotor performance is accounted for. Incoming flow onto the rotor can vary in speed and direction compared to free-stream conditions due to the presence of obstructions to the flow in the upstream, due to other devices for example, or due to the complexity

of natural bathymetries. The relative simplicity of the model leads to short run times and a lower demand on computational resources making it a useful tool for considering more complex engineering problems consisting of multiple tidal stream turbines. Results from the model compare well against both measured data from flume experiments and results obtained using the classical blade element momentum model. A discussion considering the advantages and disadvantages of these different approaches is included.

267. MASTERS, I., MALKI, R., WILLIAMS, A.J. & CROFT, T.N.: "The Influence of Flow Acceleration on Tidal Stream Turbine Wake Dynamics: A Numerical Study Using the Non-Uniformly Loaded Actuator Disk Method", *Applied Mathematical Modelling*, *vol. 37*, *issue. 16-17*, pp. 7905-7918, DOI: 10.1016/j.apm.2013.06.004, Sep-13
Studies of tidal stream turbine performance and of wake development are often conducted in tow-tanks or in regulated flumes with uniform flows across the turbine. Whilst such studies can be very useful, it is questionable as to what extent the results would differ if the flows were more complex in nature, for instance if the flows were unsteady or non-uniform or even both. This study aims to explore whether the results would be affected once we move away from the uniform flow scenario. A numerical modelling study is presented in which tidal stream turbine performance and wake development in non-uniform flow conditions are assessed. The model implements the Blade Element Momentum method for characterising turbine rotor source terms which are used within a computational fluid dynamics model for predicting the interaction between the turbines and the surrounding flow. The model is applied to a rectangular domain and a range of slopes are implemented for the water surface to instigate an increase in flow velocity along the domain. Within an accelerated flow domain wake recovery occurred more rapidly although rotor performance was not affected.

268. MCCOMBES, T., JOHNSTONE, C. & GRANT, A.: "Unsteady wake modelling for tidal current turbines", *IET Renewable Power Generation*, *vol. 5*, *issue. 4*, pp. 299-310, DOI: 10.1049/iet-rpg.2009.0203, 2011
The authors present a numerical model for three-dimensional unsteady wake calculations for tidal turbines. Since wakes are characterised by the shedding of a vortex sheet from the rotor blades, the model is based on the vorticity transport equations. A vortex sheet may be considered a jump contact discontinuity in tangential velocity with, in inviscid hydrodynamic terms, certain kinematic and dynamic conditions across the sheet. The kinematic condition is that the sheet is a stream surface with zero normal fluid velocity; the dynamic condition is that the pressure is equal on either side of the sheet. The dynamic condition is explicitly satisfied at the trailing edge only, via an approximation of the Kutta condition. The shed vorticity is the span-wise derivative of bound circulation, and the trailed vorticity is the time derivative of bound circulation, and is convected downstream from the rotors using a finite-volume solution of vorticity transport equations thus satisfying the kinematic conditions. Owing to an absence in the literature of pressure data for marine turbines, results from the code are presented for the NREL-UAE Phase IV turbine. Axial flow cases show a close match in pressure coefficients at various spanwise stations; however, yawed flow cases demonstrate the shortcomings of a modelling strategy lacking viscosity.

269. MCKINLEY, A., HENRY, A., NICHOLSON, J., ELSAESSER, B. & WINDT, C.: "The structural response of an oscillating wave surge converter to wave slamming", *International Conference on Offshore Renewable Energy, Glasgow, United Kingdom*, 15-17 Sep 2014
This paper describes the problems in experimentally obtaining hydrodynamic loads on an oscillating wave surge converter during slamming events, with the aim of furthering understanding of full scale hydrodynamic loads that flap type devices must be designed to withstand. Including how hydro-elastic effects and structural response are linked and why they are essential to the measurement of impulsive hydrodynamic loads. A combined experimental and numerical structural response study carried out on a 40th scale Oyster model drew conclusions on the structural vibration observed in the strain gauge load cell measurement. A further structural response study on a piezo electric load measurement device gave an insight into the advantages it could bring to reducing hydro-elastic effects.

270. MCNAUGHTON, J. ROLFO, S., APSLEY, D., AFGAN, I. STANSBY, P. & STALLARD, P.: "CFD Prediction of Turbulent Flow on a Laboratory Scale Tidal Stream Turbine using RANS modelling", *1st Asian Wave and Tidal Energy Conference, Jeju Island, Korea*, 27-29 Nov 2012
A detailed computational fluid dynamics (CFD) study of a laboratory scale tidal stream turbine(TST) is presented. Three separate Reynolds Averaged Navier Stokes (RANS) models: the k - ε and k- ω SST eddy-viscosity models, and the Launder-Reece-Rodi(LRR)Reynolds stress model, are used to simulate the turbulent flow-field using a new sliding-mesh method implemented in EDF's open-source Computational Fluid Dynamics solver, Code_Saturne. Validation of the method is provided through a comparison of power and thrust measurements for varying tip-speed ratios (TSR). The SST and LRR models yield results within several percent of experimental values, whilst the k- ε model significantly under-predicts the force coefficients. The blade and turbine performance for each model is examined to identify the quality of the predictions. Finally, detailed modelling of the turbulence and velocity in the

near and far wake is presented. The SST and LRR models are able to identify tip vortex structures and effects of the mast as opposed to the standard k- ε model.

271. MCNAUGHTON, J., AFGAN, I., APSLEY, D.D., ROLFO, S., STALLARD, T. & STANSBY, P.K.: "A simple sliding-mesh interface procedure and its application to the CFD simulation of a tidal-stream turbine", *International Journal on Numerical Methods in Fluids*, *vol. 74*, pp. 250-269, DOI: 10.1002/fld.3849, 10-Oct-13
An effective way of using computational fluid dynamics (CFD) to simulate flow about a rotating device—for example, a wind or marine turbine—is to embed a rotating region of cells inside a larger, stationary domain, with a sliding interface between. This paper describes a simple but effective method for implementing this as an internal Dirichlet boundary condition, with interfacial values obtained by interpolation from halo nodes. The method is tested in two finite-volume codes: one using block-structured meshes and the other unstructured meshes. Validation is performed for flow around simple, isolated, rotating shapes (cylinder, sphere and cube), comparing, where possible, with experiment and the alternative CFD approach of fixed grid with moving walls. Flow variables are shown to vary smoothly across the sliding interface. Simulations of a tidal-stream turbine, including both rotor and support, are then performed and compared with towing-tank experiments. Comparison between CFD and experiment is made for thrust and power coefficients as a function of tip-speed ratio (TSR) using Reynolds-averaged Navier–Stokes turbulence models and large-eddy simulation (LES). Performance of most models is good near the optimal TSR, but simulations underestimate mean thrust and power coefficients in off-design conditions, with the standard k– ϵ turbulence model performing noticeably worse than shear stress transport k– ω and Reynolds-stress-transport closures. LES gave good predictions of mean load coefficients and vital information about wake structures but at substantial computational cost. Grid-sensitivity studies suggest that Reynolds-averaged Navier–Stokes models give acceptable predictions of mean power and thrust coefficients on a single device using a mesh of about 4 million cells.

272. MORRIS, C.E., MASON-JONES, A., O'DOHERTY, D.M. & O'DOHERTY, T.: "The Influence of Solidity on the Performance Characteristics of a Tidal Stream Turbine", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
The performance characteristics of a tidal stream turbine are critical when assessing its economical viability. The solidity of the rotor, which is a function of the blade chord length and the number of blades, will affect the performance characteristics, from both a power output and a structural loading viewpoint. This paper investigates the influence of solidity on the performance characteristics of a horizontal axis tidal turbine using experimentally validated CFD models. The solidity was varied by altering the number of blades in the numerical models. Increasing the solidity was found to increase the peak Cθ and peak Cp and reduce the λ at which these occur. Ct was found to be approximately the same at peak Cp which was assumed to be the normal operating condition. At λ above peak Cp, near freewheeling, Ct continued to increase for the 2 bladed turbine, remained approximately constant for the 3 bladed turbine and decreased for the 4 bladed turbine, indicating that higher solidity rotors would have to withstand lower loads in the event of a failure. In addition, the thrust per blade was shown to increase with a reduction in the number of blades.

273. MORRIS, C.E., MASON-JONES, A., O'DOHERTY, D.M., TATUM, S.C., O'DOHERTY, T. & THOMPSON, D.S.: "Evaluation of the Swirl Characteristics of a Tidal Stream Turbine Wake", *10th EWTEC Conference, Aalborg, Denmark*, DOI: 10.1016/j.ijome.2015.08.001, 2-5 Sep 2013
Tidal stream turbines (TSTs) produce a rotating downstream wake. This paper describes the characteristics of the swirl flow in the wake of a TST with a view of comparing these against classical swirl theory and investigating whether swirl is an important factor in wake recovery prediction. Using computational fluid dynamics the paper describes the characteristics of velocities, pressure drop, viscosity and swirl number of 2, 3 and 4 bladed TSTs. To provide confidence in the results the characteristics are compared to the findings in the literature for a set of generic swirl generators. The swirl numbers for the TSTs in a 3.08 m/s tidal (plug) flow were found to be between 0.14 and 0.28, which describes a weak or very weak swirl flow. Whilst the characteristics are in agreement with theory it also means that the swirl component of the wake is not coupled with the axial component and cannot be used to estimate the wake length. However, peak swirl number for the 4 bladed turbine is close to the threshold of 0.3 at which axial velocity starts to become coupled with tangential velocity and therefore wake recovery may be related to S for some turbine designs.

274. NEILL, S. ET AL.: "Wave power variability over the northwest European shelf seas", *Applied Energy*, *vol. 106*, pp. 31-46, DOI: 10.1016/j.apenergy.2013.01.026, Jun-13
Regional assessments of the wave energy resource tend to focus on averaged quantities, and so provide potential developers with no sense of temporal variability beyond seasonal means. In particular, such assessments give no indication of inter-annual variability – something that is critical for determining the potential of a region for wave energy convertor (WEC) technology. Here, we apply the third-generation wave model SWAN (Simulating Waves Nearshore) at high resolution to assess the wave resource of the northwest European shelf seas, an area where many wave energy test sites exist, and where many wave energy projects are under development. The model is

applied to 7 years of wind forcing (2005–2011), a time period which witnessed considerable extremes in the variability of the wind (and hence wave) climate, as evidenced by the variability of the North Atlantic Oscillation (NAO). Our simulations demonstrate that there is much greater uncertainty in the NW European shelf wave resource during October–March, in contrast to the period April–September. In the more energetic regions of the NW European shelf seas, e.g. to the northwest of Scotland, the uncertainty was considerably greater. The winter NW European shelf wave power resource correlated well with the NAO. Therefore, provided trends in the NAO can be identified over the coming decades, it may be possible to estimate how the European wave resource will similarly vary over this time period. Finally, the magnitude of wave power estimated by this study is around 10% lower than a resource which is used extensively by the wave energy sector – the Atlas of UK Marine Renewable Energy Resources. Although this can partly be explained by different time periods analysed for each study, our application of a third-generation wave model at high spatial and spectral resolution significantly improves the representation of the physical processes, particularly the non-linear wave-wave interactions.

275. NEILL, S.P., HASHEMI, M.R. & LEWIS, M.J.: "Tidal energy leasing and tidal phasing", *Renewable Energy*, *vol. 85*, pp. 580-587, DOI: 10.1016/j.renene.2015.07.016, Jan-16
In addition to technical and economic constraints, tidal energy leasing is generally governed by demand for sites which contain the highest tidal streams, and does not take into account the phase relationship (i.e. the time lag) between sites. Here, the outputs of a three-dimensional tidal model are analysed to demonstrate that there is minimal phase diversity among the high tidal stream regions of the NW European shelf seas. It is therefore possible, under the current leasing system that the electricity produced by the first generation of tidal stream arrays will similarly be in phase. Extending the analysis to lower tidal stream regions, we demonstrate that these lower energy sites offer more potential for phase diversity, with a mean phase difference of 1.25 h, compared to the phase of high energy sites, and hence more scope for supplying firm power to the electricity grid. We therefore suggest that a state-led leasing strategy, favouring the development of sites which are complementary in phase, and not simply sites which experience the highest current speeds, would encourage a sustainable tidal energy industry.

276. NEILL, S.P., HASHEMI, M.R. & LEWIS, M.J.: "A 3D model of asymmetry in the Orkney tidal energy resource", *3rd Oxford Tidal Energy Workshop, Oxford, United Kingdom*, 7-8 April 2014
One factor that is not routinely considered in tidal energy site selection, yet which has an important role in quantifying the resource, is tidal asymmetry. Here, we present theory and develop a high-resolution 3D ROMS tidal model of Orkney to examine net power output for a range of sites along an energetic channel which exhibits varying degrees of tidal asymmetry. Since power output is related to velocity cubed, even small asymmetries in velocity lead to substantial asymmetries in power output. We also use the 3D model to assess how tidal asymmetry changes with height above the bed, i.e. representing different device hub heights, how asymmetry affects turbulence properties, and how asymmetry is influenced by wind-driven currents.

277. PAYNE, G., STALLARD, T. & MARTINEZ, R.: "Experimental Investigation of Tidal Rotor Loading due to Wave, Current and Impact with Sea Animals", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Extreme loading and associated survivability are key aspects of tidal turbines. This study focuses on the experimental investigation of extreme loads due to combined wave and current hydrodynamic loading and impact loads arising from collision with large sea animals. The design process and commissioning for reduced scale experiments to quantify such loads is described and preliminary findings are presented. The tidal device considered is a generic three bladed horizontal axis turbine. The scale of the model is approximately 1/15 relative to a typical full-scale turbine. The rotor is designed so that the thrust and power coefficient as a function of tip speed ratio represent a full-scale prototype and prior experiments. Blade design was carried out by combining an in-house blade element momentum code with a finite element analysis. Impact loads were estimated using a separate experimental apparatus consisting of a rotating arm, with similar inertia to that of the rotor, which hits a target with similar mechanical properties to those of a marine animal. Preliminary analysis indicates that impact loads are higher than hydrodynamic loads, by a factor of more than fifty for impact with a hard object. Impact with a deformable object, representing blubber of a marine, are lower but indicate negligible dependence on object mass and are greater than the predicted hydrodynamic loads. Experimental results from this campaign of tests will serve as benchmark data to validate computational fluid dynamics (CFD) of hydrodynamic loading and smooth particle hydrodynamic lattice spring modelling (SPH-LSM) of impact loading.

278. RAHMATI, M. T. & AGGIDIS, G.A.: "Numerical and experimental analysis of the power output of a point absorber wave energy converter in irregular waves", *Ocean Engineering*, *vol. 111*, pp. 483–492, DOI: 10.1016/j.oceaneng.2015.11.011, 01-Jan-16
This paper examines the optimum power output of a pitching-surge point absorber wave energy converter in irregular wave climates. A mathematical model based on frequency domain is used as the first step to estimate the hydrodynamic parameters of the device and its potential power output in realistic sea waves. The numerical

results predict that the point absorber energy converter has the potential to absorb more energy than what is contained in its own geometrical width. The optimum power of the device is then obtained from wave tank experiments in irregular wave climates. The comparison of numerical and experimental results demonstrates that the frequency domain method based on linear theory will lead to an overestimation of the energy absorption for this device. The frequency domain method provides an upper estimate for wave energy absorption due to the non-linear, viscous effects and constrained amplitude of device oscillation. However, comparison of the performance of the device with other point absorber wave energy converters shows that this wave energy converter is one of the most efficient in terms of absorbing wave energy.

279. RANSLEY, E., BROWN, S., GREAVES, D., HINDLEY, S., WESTON, P., GUERRINI, E. & STARZMANN, R.: "RANS-VOF Modelling of Floating Tidal Stream Systems", *Proceedings of the 5th Oxford Tidal Energy Workshop, Oxford, UK.*, 21-22 March 2016
A fully nonlinear coupled CFD approach has been developed to simulate the behaviour and power output of a floating tidal stream concept. The model includes RANS-VOF and rigid body solvers based on OpenFOAM®, a hybrid-catenary mooring system and a two-way-coupled, actuator-line model for a Schottel Instream Turbine with over-speed control. Simulations are performed in spring currents at the PTEC site with and without the 1-in-1 year wave present. Results show considerable complexities beyond periodic behaviour necessitating the use of models that include the complete coupled system and hydrodynamic conditions.

280. RANSLEY, E., HANN, M., GREAVES, D., RABY, A. & SIMMONDS, D.: "Numerical and Physical Modelling of Extreme Wave Impacts on a Stationary Truncated Circular Cylinder", *10th EWTEC Conference, Aalborg, Denmark*, *ISSN: 0749-0208*, 2-5 Sep 2013
With a history of international failures, the survival envelope for wave energy convertors (WECs) has become an important consideration in the design of such systems. Potential design solutions require a better understanding of the hydrodynamics and structural loading experienced during extreme events, like rogue wave impact. This paper concerns the numerical modelling and experimental validation of extreme rogue wave interactions with a fixed truncated circular cylinder. Typical extreme waves from the intermediate depth Wave Hub site were produced at 1:30 scale in the COAST Lab Ocean basin at Plymouth University from the 100 year wave statistics using the dispersive focussing method, NewWave. A fixed 0.4m diameter cylinder with a 0.4m draft was used to represent the geometry of a generic point-absorber type WEC. Physical conditions were duplicated in a numerical wave tank, solving the fully nonlinear Navier-Stokes equations, with a free surface, using the volume of fluid (VoF) method and open source CFD library OpenFOAM®. The comparison between the results shows that the CFD software is capable of simulating extreme wave interactions with a fixed cylinder and the associated hydrodynamic phenomena very well.

281. ROBINS, P.E., NEILL, S.P., LEWIS, M.J. & WARD, S.L.: "Characterising the spatial and temporal variability of the tidal-stream energy resource over the northwest European shelf seas", *Applied Energy*, *vol. 147*, pp. P510-522, Jun-15
As devices move from full-scale prototype to commercial installations, it is important that developers have detailed knowledge of the tidal energy resource. Therefore, the spatial distribution of the tidal currents over the northwest European shelf seas has been examined to improve understanding of the tidal-stream energy resource. Using a three-dimensional hydrodynamic model (ROMS) at ~1 km spatial resolution, and applying device characteristics of the Seagen-S turbine, we show that the ratio of the amplitudes of the M2 and S2 tidal currents can lead to significant variability in annual practical power generation – variability that is not accounted for when considering only the mean peak spring tidal velocities, as is generally the case in resource feasibility studies. In addition, we show that diurnal inequalities (governed by K1 and O1 tidal constituents) and tidal asymmetries (governed by the relationship between M2 and its compound tide M4) over the northwest European shelf seas can further affect power generation at potential high-energy sites. Based on these variabilities, the spatial distribution of the tidal-stream ‘capacity factor’ has been calculated. We find that mean peak spring tidal velocities can under-estimate the resource by up to 25%, and that annual practical power generation can vary by ~15% for regions experiencing similar mean peak spring tidal velocities, due to the influence of other tidal constituents. Therefore, even preliminary resource assessments should be based on annual average power density, rather than peak spring tidal velocity.

282. RODRIGUEZ, M. & SPINNEKEN, J.: "A laboratory study on the loading and motion of a heaving box", *Journal of Fluids and Structures*, *vol. 64*, pp. 107-126, DOI: 10.1016/j.jfluidstructs.2016.05.001, *ISSN: 1095-8622*, Jul-16
This paper concerns the nonlinear loading and dynamic response of a heaving rectangular box in two dimensions, using a series of experimental tests in regular and irregular wave conditions. Nonlinear forcing components are found to make major contributions to both the excitation problem and the motion response. Two main sources of nonlinearity are established: the first associated with higher-order wave–structure interactions, and the second

associated with viscous dissipation. The present work quantifies the relative influence of these two sources. Adopting a series of regular wave cases, the first source, prevalent in steep wave conditions, is shown to be particularly significant in the diffraction regime, leading to significant excitation force amplifications. In deep water, these nonlinearities are primarily driven by interactions between incident and reflected wave components. The second source, due to vortex shedding, plays a minor role in the excitation problem, but has a major influence on the motion response. Vortex-induced effects are particularly important when the structure exhibits large motions, for example at resonance. To characterise the response in irregular waves, experimental data are provided comprising in excess of 100,000 individual waves, presenting one of the most substantial data sets of this kind to date. In considering these irregular sea states, the two aforementioned sources of nonlinearity are again found to be of critical importance. While wave-induced load amplifications of up to 60% may be observed in the excitation problem, the motion response is primarily governed by vortex-induced attenuations. In order to provide practical engineering solutions, two approaches are offered. For nonlinear forcing predictions, a two parameter Weibull fit is found to be both simple and accurate. In terms of the heave motion, a computationally efficient time-domain simulation, building upon a linear hydrodynamic description and a quadratic MOJS type drag term, leads to good agreement with experimental data.

283. RODRIGUEZ, M., SPINNEKEN, J. & SWAN, C.: "Nonlinear loading of a two-dimensional heaving box", *Journal of Fluids and Structures*, *vol. 60*, pp. 80-96, DOI: 10.1016/j.jfluidstructs.2015.11.001, *ISSN: 0889-9746*, Jan-16

A numerical investigation is presented addressing the nonlinear heave response of a rectangular box. The work specifically concerns the importance of the relative body dimensions, expressed through the product of the half-beam b and the wavenumber k. When subjected to moderately steep incident waves, the second-harmonic content of the heave motion is found to be as large as 25% of the first-harmonic content. In considering the extent of this second-harmonic motion, three regimes may be defined: (i) the long wave regime, where $kb \leq 0.4$, (ii) the intermediate regime, where $0.4<kb<1$ and (iii) the diffraction or short wave regime, where $kb \geq 1.0$. Expressed in terms of the wavelength $\lambda=2\pi/k$, these regimes correspond to (i) $b \leq 0.06\lambda$, (ii)$0.06\lambda<b<0.16\lambda$ and (iii) $b \geq 0.16\lambda$. The second-harmonic motion content is found to be particularly pronounced in regimes (i) and (iii). Perhaps surprisingly, this second-harmonic content is also found to be practically non-existent for some intermediate cases lying within regime (ii). Three sources of nonlinearity are shown to be particularly important. First, the interaction between the first-order incident waves and the first-order scattered waves is key to the nonlinear loading in regime (iii). Second, the generation of freely propagating second-harmonic radiated waves due to the body motion is important in (i). Third, the local standing wave field associated with the radiation problem is found to contribute to the loading in regime (iii). In addition, the location of the body resonance also plays a critical role in defining the extent of the second-harmonic motion content. The focus of the present work lies on a clear physical interpretation of the sources of these nonlinear loads, coupled with an analysis of the body dynamics.

284. RODRÍGUEZ, M., SPINNEKEN, J. & SWAN, C.: "Fully-nonlinear loading on a two-dimensional heaving box", *Journal of Fluids and Structures*, *vol. 60*, pp. 80-96, 2014

A numerical investigation is presented addressing the nonlinear heave response of a rectangular box. The work specifically concerns the importance of the relative body dimensions, expressed through the product of the half-beam b and the wavenumber k. When subjected to moderately steep incident waves, the second-harmonic content of the heave motion is found to be as large as 25% of the first-harmonic content. In considering the extent of this second-harmonic motion, three regimes may be defined: (i) the long wave regime, where $kb \leq 0.4$, (ii) the intermediate regime, where $0.4<kb<1.0$ and (iii) the diffraction or short wave regime, where $kb \geq 1.0$. Expressed in terms of the wavelength $\lambda=2\pi/k$, these regimes correspond to (i) $b \leq 0.06\lambda$, (ii)$0.06\lambda<b<0.16\lambda$ and (iii) $b \geq 0.16\lambda$. The second-harmonic motion content is found to be particularly pronounced in regimes (i) and (iii). Perhaps surprisingly, this second-harmonic content is also found to be practically non-existent for some intermediate cases lying within regime (ii). Three sources of nonlinearity are shown to be particularly important. First, the interaction between the first-order incident waves and the first-order scattered waves is key to the nonlinear loading in regime (iii). Second, the generation of freely propagating second-harmonic radiated waves due to the body motion is important in (i). Third, the local standing wave field associated with the radiation problem is found to contribute to the loading in regime (iii). In addition, the location of the body resonance also plays a critical role in defining the extent of the second-harmonic motion content. The focus of the present work lies on a clear physical interpretation of the sources of these nonlinear loads, coupled with an analysis of the body dynamics.

285. SANKARAN IYER, A., COUCH, S.J., HARRISON, G.P. & WALLACE, A.R.: "Quantifying the Impact of Tidal Current Energy Variability and Matching UK Demand", *4th International Conference on Ocean Energy (ICOE) 2012, Dublin, Ireland*, 17-19 Oct 2012

Electricity demand varies over time and this variability can be defined over short timescales of seconds to longer durations of weeks and seasons. Trends of demand patterns have been studied to better understand energy

consumption in the UK. Studying these trends helps inform prediction of future demand over short and long term based on current understanding. Introduction of renewables into the electricity network can cause a number of issues related to generation intermittency. However a systematic approach can address the issues of network integration and matching electricity demand with supply. Due to its predictable nature, energy harnessed from tidal currents can be predicted to a high level of accuracy well into the future. The aim of this study is to explore the availability of economically viable tidal current energy within UK territorial waters, and examines the timings of tidal generation with respect to electricity demand. This is achieved through development of realistic build-out 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.

286. SANTO, H., TAYLOR, P.H., WOOLLINGS, T. & POULSON, S.: "Decadal wave power variability in the North-East Atlantic and North Sea", *Geophys. Res. Lett.*, *vol. 42*, pp. 4956-4963, DOI: 10.1002/2015GL064488, 2015
Estimation of the long-term behavior of wave climate is crucial for harnessing wave energy in a cost-effective way. Previous studies have linked wave heights to the north-south atmospheric pressure anomalies in the North Atlantic, suggesting that the wave climate fluctuates as a response to changes in zonal circulation in the atmosphere. We identify changes in wave power in the North-East Atlantic that are strongly correlated to the dominant pressure anomalies, the North Atlantic Oscillation (NAO), and other modes. We present a reconstructed wave power climate for 1665–2005, using a combination of known and proxy indices for the NAO and other modes. Our reconstruction shows high interannual and multidecadal variability, which makes wave energy prediction challenging. This variability should be considered in any long-term reliability analysis for wave energy devices and in power scheme economics.

287. SHEK, J., DORRELL, D., HSIEH, M., LIN, I.H., MOSTAFA, K., MUELLER, M. & YEH, Y.H.: "Unbalanced Forces in Electrical Generators for Wave and Tidal Devices", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Electrical generators and other drive train components experience significant varying loads in wave and tidal devices. This can lead to bearing failure due to unbalanced forces caused by misalignment and rotor eccentricity. For wave and tidal devices to operate effectively components, such as bearings, should be repaired or replaced prior to failure. This paper presents modelling of an electrical generator to investigate the unbalanced forces produced and the experimental test rig design that will verify simulation work. Work from the paper will lead towards a drive-train bearing wear model where unbalanced forces can be reduced and failures minimised.

288. STAGONAS, D., BULDAKOV, E. & SIMONS, R.: "Focussing unidirectional wave groups on finite water depth with and without currents", *34th International conference on Coastal Engineering, ASCE, Seoul, Korea*, 15-20 June 2014
Focused waves are often used in physical and numerical studies as a representative condition for extreme waves or as a mean to generate very steep and breaking waves at a desired location in space and time. A focused wave is in theory created when all the components in a transient wave group come in phase. In the past, linear wave theory and empirical iterative methodologies have been suggested in order to achieve the required phase and amplitude focusing. Nevertheless, their effectiveness decreases as the non-linearity of the wave group increases and thus the generation of very high focused waves was a challenging task. Here, an empirical iterative methodology is suggested which can focus waves of any height at a predetermined temporal and spatial location. The methodology has been successfully applied to wave groups travelling on still water but also on sheared currents and it has been implemented in both physical and numerical wave flumes. The results presented here refer to linear, weakly non-linear and strongly non-linear focused waves generated with a realistic target spectrum.

289. STALLARD, T., FENG, T. & STANSBY, P.: "Experimental Study of the Mean Wake of a Tidal Stream Rotor in a Shallow Turbulent Flow", *Journal of Fluid Structures*, *vol. 54*, pp. 235-246, DOI: 10.1016/j.jfluidstructs.2014.10.017, Apr-15
The mean wake of a three-bladed horizontal axis tidal stream turbine operating at maximum power coefficient has been investigated experimentally in a wide flume with width 11 times the depth, providing minimal restriction to transverse wake development and behaviour of large-scale horizontal turbulence structures. This is an important first stage for understanding wake interaction in turbine arrays and hence large-scale power generation. The rotor diameter has a typical value of 60% of the depth and the thrust coefficient is representative of a full-scale turbine. The shear layers originating from the rotor tip circumference show classic linear expansion downstream, with the rate of a plane shear layer vertically and 1.5 times that horizontally. These shear layers merge by around 2.5 diameters downstream forming a self-similar two-dimensional wake beyond eight diameters downstream with a virtual origin at two diameters downstream of the rotor plane. The spreading rate is somewhat less than that for solid bodies. The detailed velocity measurements made in the near wake show rotation and vorticity similar to that

measured previously for wind and marine turbines although with asymmetry associated with bed and surface proximity. The longitudinal circulation in a transverse plane is conserved at about 1% of the swept circulation from the blade tip within two diameters downstream, the extent of detailed measurement. Turbines are usually designed using blade element momentum theory in which velocities at the rotor plane are characterised by axial and tangential induction factors and it is now possible to see how this idealisation relates to actual velocities. The axial induction factor corresponds to velocity deficits at 0.4–0.8 radii from the rotor axis across the near wake while the tangential induction factor at the rotor plane corresponds to velocities at 0.4–0.6 radii between 1–2 diameters downstream, indicating some general correspondence. For the two-dimensional self-similar far wake the two parameters defining the centreline velocity deficit and the transverse velocity profiles are likely to be insensitive to Reynolds number in turbulent conditions.

290. STANSBY, P.K., DEVANEY, L.C. & STALLARD, T.J.: "Breaking wave loads on monopiles for offshore wind turbines and estimation of extreme overturning moment", *IET Renewable Power Generation*, *vol. 7*, *issue. 5*, pp. 514-520, DOI: 10.1049/iet-rpg.2012.0205, 2013
Measurements of breaking wave forces on vertical circular columns have been re-analysed, where substantial magnification over forces because of non-breaking non-linear waves may occur, by a factor of up to 2.8. The analysis shows that this factor increases as the depth parameter kd decreases, being close to unity for kd > 1.5 (k is the wave number and d is depth). Non-breaking wave forces are predicted reasonably by non-linear stream function wave theory using Morison's equation with empirical drag and inertia coefficients. A study was then made of the magnitude of wave overturning moment in relation to hub moment due to wind on standard 2 and 5 MW turbines with a 6 m diameter column. This showed that the wave moment in extreme conditions is greater than wind 'hub' moment for depths greater than about 7 and 13 m for the 2 and 5 MW turbines, respectively. Monopiles are normally used in depths below about 30 m and extreme moments due to waves occur when waves are depth-limited and defined by the Miche criterion, well below the limiting value of kd for the onset of depth-induced breaking. The maximum moment for these depths is expected to be predicted reasonably.

291. SUDALL, D., STALLARD, T. & STANSBY, P.K.: "Energy Yield for Collocated Offshore Wind and Tidal Stream Farms", *European Wind Energy Conference, Copenhagen, Denmark*, 10-12 March 2015
Deployment of co-located wind and tidal stream turbines is proposed as a method for reducing cost of electricity generation from either technology individually. Energy yield for wind turbines is modelled using an eddy viscosity wake model and for tidal turbines using a method of self-similar superposition of wake deficits. Yaw strategy is considered for the tidal turbines, finding that although a continuous yaw strategy generates highest yield, a slack-tide strategy offers a suitable compromise with mechanical complexity. A case-study of the MeyGen site in the Pentland Firth is considered for co-location. The addition of 12MW of wind capacity to a 20MW tidal array results in a twofold increase in annual energy yield, compared to operating the tidal turbines alone. Phasing of the tidal cycle means that during a neap tide, the combined system may be entirely dependent on wind generation, but during a spring tide there is a regular tidal supply. Steady state loads for wind and current are also modelled for a braced monopile support structure. For tidal turbines only, the mean probable loads vary by 12% across the array. Net horizontal force on the tidal turbines is 28% greater than on the wind turbines. However, due to the distance between turbine axis and base, the magnitude of the base moment for the combined support structure is found to be driven by wind loading.

292. SUFIAN, S. & LI, M.: "3D-CFD numerical modelling of impacts from horizontal axis tidal turbines in the near region", *34th International conference on Coastal Engineering, ASCE, Seoul, Korea*, 15-20 June 2014
A Virtual Blade Model approach has been applied to simulate flows across a Horizontal Axis Tidal Turbine (HATT). The 3DCFD Fluent 14.5 package was employed to solve the Reynolds Averaging Navier Stokes equations. A source term was added in the momentum equation as part of the solution developed through the Blade Element Momentum Theory for an incompressible flow in a open channel. The model was validated against experimental data of a 3 bladed 0.5m diameter turbine in a high speed re-circulating water flume in terms of velocity and Turbulent Kinetic Energy (TKE) profiles. The model results correlate well with the experimental data. The change of flow field and the variation of free surface can be clearly seen in the results.

293. SUTHERLAND, D.R.J., SELLAR, B.G., HARDING, S. & BRYDEN, I.: "Initial Flow Characterisation Utilising Turbine and Seabed Installed Acoustic Sensor Arrays", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Flow velocity measurements from acoustic sensors mounted both on mid-channel depth tidal turbines and on the seabed are presented for the Fall of Warness in Orkney. The tides are analysed in one hour phases in order to investigate the evolution of metrics over the semi-diurnal cycle. The site is characterised by mean velocity magnitudes and their variation with depth, velocity direction and corresponding variation with depth (twist of the depth profile) and the turbulence intensity and its variation with depth. Analysis shows the maximum velocities of the tides at the site to be within 4 ◦ of bi-directionality at a reference 'point' 13 m above the turbine with the ebb tide exhibiting greater velocity magnitude as expected from previous site surveys. Variation between the tides is

also evident in the twist of the depth profiles which is more pronounced in the slower flood tide, up to a maximum of 7 ◦ between the turbine and the surface. In general, both twist of the depth profile and directional variation is greatest at the lowest flow speeds. Mean turbulence intensity is shown to increase near the surface despite no significant drop in the mean velocity, particularly for the ebb tide, indicating wave orbital motion may play a role in near surface fluctuations. Finally a comparison of newly available data from a seabed-deployed ADCP with a Turbine mounted sensor shows a similar velocity depth profile curve but with a mean velocity deficit that is inconsistent over the diurnal cycle. The spatial variation of velocity (and consequent loading) over the rotor.

294. TATUM, S.C., ALLMARK, M., FROST, C.H., O'DOHERTY, D.M., MASON-JONES, A. & O'DOHERTY,T.: "CFD modelling of a tidal stream turbine subjected to profiled flow and surface gravity waves", *EWTEC conference, Nantes, France*, DOI: 10.1016/j.ijome.2016.04.003, 7-10 Sep 2015
This study used computational fluid dynamics to investigate the effect of waves and a velocity profile on the performance of a tidal stream turbine (TST). A full scale TST was transiently modelled operating near its maximum power point, and then subjected to waves both in and out of phase with its period of rotation. A profile was then added to one of the wave models. For this set of conditions it was found that the longer period and in-phase wave had a significant effect on the power range fluctuations, with more modest variations for thrust and the average values, although this is dependent on the turbine tip speed ratio. The addition of the profile had a strong effect on the bending moment. It has been concluded that a naturally varying sea state may yield a smoothing effect in this turbine response, but that with further structural investigation it may be that some measuring and mitigation techniques are required in the event of a predominantly single long period, in-phase wave.

295. TATUM, S.C., FROST, C.H., ALLMARK, M., O'DOHERTY, D.M., MASON-JONES, A., PRICKETT, P.W., GROSVENOR, R.I., BYRNE, C.B. & O'DOHERTY,T.: "Wave –Current Interaction Effects on Tidal Stream Turbine Performance and Loading Characteristics", *International Journal of Marine Energy*, DOI: 10.1016/j.ijome.2015.09.002, 2015
The transient interaction between tidal currents and the rotation of a horizontal axis turbine rotor have the potential to induce high asymmetric loadings, which are subsequently transmitted to the drive shaft and potentially high speed drive train components. To mitigate the potential for early component failure, analysis of asymmetric loading on marine turbines is fundamental to the design process. To investigate these loads a turbine mounted on a circular stanchion has been used to highlight the effects of introducing more realistic boundary conditions. Depending on their wavelength, waves can also have a significant effect on the overall design decisions and placement of devices. Thrust loading and bending moments applied to the drive shaft can be of the order of hundreds of kN and kNm respectively. Knowledge of the flow regime can allow designers to evaluate material selection for components and incorporate some deformation capability of the turbine blades to increase the power output and potentially alleviate some of the stress distribution through key structural points. The resulting data can then be used to estimate component life via fatigue prediction. This paper includes a multi-physics approach to modelling tidal energy devices and the potential for modelling to inform device condition monitoring.

296. TEDDS, S.C., DE JESUS HENRIQUES, T.A., OWEN, I. & POOLE, R.J.: "Near-wake characterisation of Horizontal Axis Tidal Stream Turbines in non-uniform steady flow", *National Oceanography Centre "Liverpool Marine Symposium", Liverpool, United Kingdom*, 28-Jan-14
A detailed experimental study has been completed to characterise the near-wake of a model three-bladed Horizontal Axis Tidal Stream Turbine (diameter = 0.5m). The turbine was tested at the University of Liverpool high-speed water channel. A non-uniform "flow-profiler" has been developed, using a series of 16mm horizontal bars, to produce a 1/5th power-law vertical velocity profile in the channel. The integral average upstream velocity, over the turbine swept area, was set to 0.82m/s and had an average turbulence intensity of approximately 5%. Power and thrust measurements from the turbine are compared to results in uniform flow. When plotted non-dimensionally, using the integral average velocity, the power and thrust for both the uniform and non-uniform flow are seen to be the same. To provide details of the flow emerging from the turbine, measurements of the nearwake have been taken using an Acoustic Doppler Velocimeter. These were taken up to five diameters downstream of the turbine over a series of spanwise profiles at various depths to fully map the near-wake flow field. The flow characteristics of the nearwake downstream of the turbine in non-uniform flow is similar to previous results with uniform flow. It is shown that in both flow conditions the swirl from the rotation of the turbine is very prominent and is still significant at 5 diameters downstream.

297. TEDDS, S.C., OWEN, I. & POOLE, R.J.: "Near-wake characteristics of a model Horizontal Axis Tidal Stream Turbine", *Renewable Energy*, *vol. 63*, pp. 222-235, DOI: 10.1016/j.renene.2013.09.011, 2014
The results of a detailed experimental investigation of the near-wake (up to seven turbine diameters downstream) of a model horizontal axis tidal turbine (HATT) device in a large-scale recirculating water channel facility are reported. An Acoustic Doppler Velocimeter is used to provide detailed three-dimensional mean and turbulent flow field information at five different depths across the full width of the channel downstream of the turbine, giving the

most complete three-dimensional velocities and Reynolds normal and shear stress data set yet available. In addition the Reynolds-stress anisotropy tensor is used to illustrate the degree of anisotropy of the Reynolds stress within the turbine's wake. These results reveal the strongly anisotropic nature of the near-wake turbulence suggesting isotropic turbulence models should not be used to model near-wake dynamics. Finally the power-law decay rates of the maximum normalised turbulent kinetic energy differ significantly from those found downstream of grids, meshes or perforated disks, suggesting that previous modelling approaches, which neglected swirl effects and modelled the turbine by absorption discs, may significantly over predict the turbulent kinetic energy decay rate of HATT wakes.

298. THIES, P.R., JOHANNING, L., GORDELIER, T. & WELLER, S.: "Physical component testing to simulate dynamic marine load conditions", *32nd International Conference on Ocean, Offshore and Arctic Engineering, Nantes, France*, 9-14 June 2013
The reliability and integrity of components used in the marine offshore environment is paramount for the safety and viability of offshore installations. The engineering challenge is to design components that are robust enough to meet reliability targets whilst lean enough to minimise cost. This is particularly the case for offshore marine renewable installations which operate in the same, possibly harsher, environment as offshore oil and gas installations, and are subjected to highly cyclic and dynamic wave, wind and operational load conditions. The cost of electricity produced has to compete with other means of electricity generation and does thus not offer the same profit margins available as oil and gas commodities. As a result, components for marine renewable installations have to meet the target reliability, without the application of costly safety factors to account for load and environmental uncertainties. Industries with similar design tasks such as the aviation or automotive industry have successfully used a service simulation test approach to develop robust yet lean designs. This paper builds on an approach to establish and validate the reliability of floating renewable energy devices in which dedicated component testing using the purpose built Dynamic Marine Component test rig (DMaC) plays a pivotal role to assess, validate and predict the reliability of components in the marine environment. This paper presents a test rig for both static and fatigue tests of marine components such as mooring lines and mooring shackles under simulated or measured load conditions and provides two case studies from recently conducted mooring component tests. This includes an investigation into the load behaviour of synthetic mooring ropes and the ageing of mooring shackles.

299. TOGNERI, M. & MASTERS, I.: "Parameterising turbulent marine flows for a blade element momentum model of tidal stream turbines", *EWTEC 2011, Southampton, UK*, Sep-11
Blade element momentum theory (BEMT) allows much more rapid modelling of turbines than full Navier-Stokes simulations. Classical BEMT greatly simplifies flow conditions to make this rapidity possible; we can, however, modify BEMT to incorporate additional flow phenomena without sacrificing much in the way of calculation speed. Using an already-existing extended BEMT model, this paper explores how turbulent flows can be synthesised in order to predict their effects on turbine performance. Artificial turbulent flows are created based on data from a bed-mounted acoustic Doppler current profiler (ADCP). Our extended BEMT model is capable of predicting the response of a tidal turbine to a real measured flow; thus we can use the predictions of this model to calibrate our model of synthetic turbulence against real turbulence measurements. The accuracy of this turbulence synthesis is assessed by examination of both turbine performance and load parameters.

300. TOGNERI, M., MASTERS, I. & ORME, J.: "Incorporating turbulent inflow conditions in a blade element momentum model of tidal stream turbines", *ISOPE conference, Hawaii, USA*, 2011
Blade element momentum theory (BEMT) is a well-established method for evaluating the performance of turbines designed to extract energy from a flowing fluid. In this paper, we discuss a modified version of BEMT that allows for greater variation in the permissible inflow conditions, paying particular attention to inflow conditions that model turbulence in coastal waters in order to calculate the power output and other performance parameters of tidal stream turbines (TSTs). In the first part of the paper, we describe the modification we have made to standard BEMT analysis. In the second part, we describe how we create an appropriate representation of a turbulent tidal stream or marine current, and what parameters we can extract from measurements of a real current in order to create this representation. Some preliminary results are presented and their significance discussed.

301. TOGNERI, M., MASTERS, I., ALLMARK, M. & ELASHA, F.: "Unsteady BEMT for fault diagnosis and prognosis in tidal stream turbines", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
We present the results of simulations carried out with a robust blade element momentum theory (BEMT) model. This model includes several modifications to classical BEMT, including the addition of tip/hub losses, high induction effects and, most importantly for this work, the ability to deal with arbitrary inflow conditions (i.e., including time variation and spatial non-uniformity). We use this capacity to simulate the response of tidal stream turbines (TSTs) to turbulent inflow conditions. The discussion presented centres firstly on the method of generating these inflow

conditions, and secondly on how the simulation results can be used both to diagnose fault conditions during TST operation, and to prognose the fatigue lifespan of gearbox components.

302. VENUGOPAL, V. & NEMALIDINNE, R.: "Marine Energy Resource Assessment for Orkney and Pentland Waters with a coupled Wave and Tidal Flow Model", *33rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, California*, 8-13 June 2014
Some preliminary results obtained from a coupled wave and 3D tidal flow numerical model, applied to the Orkney and Pentland waters in the Scottish region of the United Kingdom, are reported in this paper. The coupled wave and flow model was applied to the Orkney Islands comprising a domain of 1.25°W – 5°W and 58.25° N – 59.75°N. The model was run by boundary inputs of wind and water level extracted from European Centre for Medium Range Weather Forecasts (ECMWF) and Danish Hydraulic Institute's (DHI) global tidal model respectively. The model has been calibrated and validated with wave buoy and ADCP (Acoustic Doppler and Current Profiler) measurements. The depth-wise current velocity components predicted by the model were compared with ADCP measurements for three sites in the Pentland Firth. The results indicated that the coupled model worked well and the tidal current velocities from the model correlated well with ADCP measurements at different depths.

303. WATANABE, Y. & INGRAM, D.: "Transverse instabilities of uprising planar jets formed by wave impacts on vertical walls", *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 2015
When a steep breaking wave hits a vertical sea wall, in shallow water, a rapidly ascending planar jet forms. This jet is ejected with high acceleration due to pressure created by the violent wave impact on the wall, creating a so-called 'flip-through' event. Previous studies have focussed on the impulsive pressures on, and within, the wall and on the velocity of the jet. Here, in contrast, we consider the formation and break-up of the jet itself. Experiments show that during flip-through a fluid sheet, bounded by a rim, forms. This sheet has unstable transitional behaviours and organising jets; undulations in the thickness of the fluid sheet are rapidly amplified and ruptured into an array of vertical ligaments. Lateral undulations of the rim lead to the formation of finger-jets, which subsequently break up to form droplets and spray. We present, a linear stability analysis of the rim sheet systems that highlights the contributions of rim retraction and sheet stretching to the breakup process. The mechanisms for the sequential surface deformations in the rim-sheet system are also described. Multiple, distinct, instability modes are identified during the rim deceleration, sheet stretch attenuation and rim retraction processes. The wave numbers (and deformation length scales) associated with these instability modes are shown to lead to the characteristic double peak spectrum of surface displacement observed in the experiments. These mechanisms help to explain the columnar structures often seen in photographs of violent wave impacts on harbour walls.

304. WELLER, S., DAVIES, P., THIES, P.R., HARNOIS, V., JOHANNING, L.: "Durability of synthetic mooring lines for ocean energy devices", *4th International Conference on Ocean Energy*, 17-19 Oct 2012
The mooring systems of Marine Energy Converters (including wave energy, tidal energy and offshore floating wind systems) are critical elements and a thorough understanding of their long term durability is essential to guarantee the survivability of these devices. Synthetic fibre ropes offer advantages compared to steel in terms of handling, and can provide a wide range of mechanical and damping properties. However, their long-term behaviour is less well known. This paper will first present results from recent studies conducted for the offshore industry and discuss these in terms of renewable energy devices. A reliability-based approach will then be described, and a framework for qualifying synthetic ropes, adapted to the specific requirements of ocean energy devices, will be presented. New data from measurements at sea will be provided to support the methodology.

305. WELLER, S.D, STALLARD, T.J. & STANSBY, P.K.: "Experimental measurements of the complex motion of a suspended axisymmetric floating body in regular and near-focused waves", *Applied Ocean Research*, *vol. 39*, pp. 137-145, DOI: 10.1016/j.apor.2012.10.008, Jan-13
Numerical models which account for the multiple response modes of floating wave energy converters (WECs) in operating conditions require experimental data for validation. Measurement and observation of complex hydrodynamic mechanisms are also required to inform the development of modelling tools suitable for the simulation of response to extreme waves. Experimental measurements are reported of the motion of an axisymmetric float to regular and near-focused waves. The mechanical system, incident wave conditions and response in a 2D vertical plane are detailed to facilitate comparison to numerical simulations. The system comprises a heaving float connected to a counterweight by an inextensible cable over two pulleys to provide a simplified representation of the slowly varying surge constraint of a mooring system. Translation of the float is measured using an optical encoder. Motion in heave, surge and pitch are also determined by a position identification method based on analysis of video footage. For low frequency regular waves, the float prescribes an elliptical trajectory and the variation of response amplitude with wave amplitude is linear. At higher frequencies, drift of up to one-third of the float radius is observed and the float oscillates along an arc. More complex motions are observed due to the three large amplitude waves of a near-focused wave group. During these waves the upper surfaces of the float are partly immersed and motion occurs in heave, surge and pitch.

306. WELLER, S.D., DAVIES, P., VICKERS, A.W. & JOHANNING, L.: "Synthetic rope responses in the context of load history: Operational performance", *Ocean Engineering*, *vol. 83*, pp. 111-124, DOI: 10.1016/j.oceaneng.2014.03.010, 2014

The utilisation of synthetic mooring ropes for marine renewable energy (MRE) devices is a recent occurrence. Despite current use in the offshore industry, MRE mooring components are typically subjected to highly dynamic loads, necessitating the detailed characterisation of operational and long-term component performance for lifecycle analysis and operations management. To address the uncertainties associated with synthetic mooring components in this application, tension experiments have been conducted on nylon 6 parallel-stranded rope samples at IFREMER, France and the University of Exeter, UK under the consortium MERiFIC (Marine Energy in Far Peripheral and Island Communities). Measurements are reported from harmonic loading tests with different initial bedding-in levels used to investigate the influence of load history on the immediate dynamic properties of the rope. Two irregular load regimes were also applied based on mooring tensions recorded by the South West Mooring Test Facility (SWMTF). Datasets are provided to facilitate the development of rope modelling tools. For the load regimes studied it was found that the operational performance of the rope is strongly influenced by the instantaneous load-strain characteristic. This study provides unique insight into the stiffness and damping properties of synthetic rope in the context of loading regimes relevant to MRE devices.

307. YIN, Y., LI, M., MOULINEC, C. & EMERSON, D.: "In-depth HPC-LES investigation for the flow around a circular cylinder using TELEMAC3D", *21st Telemac and Mascaret User Conference, Grenoble, France*, 15-17 Oct 2014

Flow around a circular cylinder in laboratory scale is simulated by coastal model TELEMAC3D. The aim of this paper is to investigate the performance and accuracy of TELEMAC3D, hydrostatic mode, at laboratory scale. The model is tested on both smooth bed and rough bed conditions. The turbulence characteristics are modelled using Large Eddy Simulation and the Smagorinsky sub-grid scale model. The model results, including velocity profiles and the Strouhal number are compared with experimental data. Three different mesh sizes are used in these tests. According to the comparison, the finest mesh gives a better agreement of the model exhibiting the right trend in the wake part, comparing to the experimental data.

Fatigue Loadings and Reliability

309. AHAMED, R.A., JOHNSTONE, C. & STACK, M.M.: "Mapping blade angle effects for the erosion of polymer based composites: an approach to developing smart materials for tidal turbines.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015

Tribology in marine renewable technologies has become of increasing interest due to the implications for developing improved materials for tidal and wave energy conversion devices. For tidal devices, the materials of interest are primarily polymer based composite materials that are used to provide structural integrity while reducing weight. These are specifically applied to turbine blades to withstanding the high impact loadings in sea water conditions. At present, current materials in test trials have demonstrated some limitaions in service. In this paper, fundamental research has been carried out to investigate tribological mechanisms of potential candidate composite materials to be used in tidal turbines by firstly considering the effects of various erosion parameters on the degaradation modes, with and without particles in sea water conditions. The erosion mechanisms of composite materials used in tidal turbine blades have been evaluated using Scanning Electron Microscopy techniques to analyse the surface morphologies following testing in water representative of the constituents of costal sea water. Generic erosion maps have been constructed as a first step approach to identify regions of minimum erosion for the operating conditions and to identify the significant effect of the sea water environment on the degradation of the composite.

310. BAHAJ, A.S.: "Marine current energy conversion: the dawn of a new era in electricity production.", *Philosophical Transactions of the Royal Society Part A*, *vol. 371*, *issue. 1985*, DOI: 10.1098/rsta.2012.0500, 14-Jan-13

Marine currents can carry large amounts of energy, largely driven by the tides, which are a consequence of the gravitational effects of the planetary motion of the Earth, the Moon and the Sun. Augmented flow velocities can be found where the underwater topography (bathymetry) in straits between islands and the mainland or in shallows around headlands plays a major role in enhancing the flow velocities, resulting in appreciable kinetic energy. At some of these sites where practical flows are more than 1ms-1, marine current energy conversion is considered to be economically viable. This study describes the salient issues related to the exploitation of marine currents for electricity production, resource assessment, the conversion technologies and the status of leading projects in the field. This study also summarizes important issues related to site development and some of the approaches currently being undertaken to inform device and array development. This study concludes that, given the highlighted commitments to establish favourable regulatory and incentive regimes as well as the aspiration for energy independence and combating climate change, the progress to multi-megawatt arrays will be much faster than that achieved for wind energy development.

311. BASHIR, I., WALSH, J., THIES, P.R., BLONDEL, P. & JOHANNING, L.: "Underwater Acoustic Emission Testing of Mooring Ropes at Dynamic Marine Component Test Facility (DMaC)", *PRIMaRE Conference, Penryn, United Kingdom*, 16-Jun-15

The cost of producing energy using Wave Energy Converters (WEC) operating in harsh sea environment is directly related to the maintenance cost and reliability of the system. Acoustic Emission (AE) can provide a low-cost, remote and reliable Conditional Health Monitoring (CHM) for WEC. It will allow the continual monitoring of the engineering health of WEC, hence identifying damage before device failure. This will minimize the cost, down time and use of resources for maintenance and inspection. For 20 years AE monitoring has been developed for the detection and localization of fatigue cracks in a variety of metal structures [1], including within the wind energy sector for monitoring wind turbine blades [2]. However, AE signals are non-stationary and are often comprised of overlapping transient waves, whose waveforms and arrival times are unknown. The interpretation of AE signals and the separation of true damage sources from spurious noise is the biggest challenge in this field [3]. This problem can be minimized by using multiple sensors in an array. In order to study the AE due to mooring ropes, underwater acoustic testing has been carried out at DMaC (Dynamic Marine Component) test facility. DMaC is a purpose built test rig that replicates the forces and motions that components are subjected to in offshore applications. AE testing was carried out by submerging the polyester ropes in water and applying cyclic tensile loading. A three hydrophone line-array was placed alongside the rope to identify the initialization of fatigue damage and its point of origin. Continuous recording was carried out at a sampling rate of 96 kHz for each 20 minute test schedule. The maximum cyclic tensile load was increased linearly to study the rope response. The first AE click was identified when the maximum cyclic load was at 75 kN, however the rope completely failed at 98 kN. The number and intensity of the recorded clicks were found to be directly proportional to the tensile loading. The recorded clicks provide a very broadband spectrum, i.e. 50 Hz – 48 kHz. By using triangulation and time of arrival estimation at the three hydrophones, the clicks origin was pinpointed. Further clicks and the location of complete failure were found to be at this same location. Consequently the weak point in the mooring rope was identified

much earlier in its lifetime than the actual failure. This initial testing shows promising results that are repeatable and consistent across multiple rope samples.

312. BASUMATARY, J., NIE, M. & WOOD, R.J.K.: "The synergistic effects of cavitation erosion-corrosion in ship propeller materials", *Journal of Bio- and Tribo-Corrosion*, *vol. 1*, *issue. 12*, pp. 1-12, *ISSN: 2198-4220*, 2015
Synergy tests were performed for two most common propeller materials, duplex stainless steel (DSS) and nickel aluminium bronze (NAB), by means of an indirect ultrasonic vibratory system. Tests were conducted for pure cavitation erosion in distilled water, pure corrosion using in situ electrochemistry under 3.5 % NaCl solution and a combination of cavitation erosion–corrosion to understand the overall synergism existing between the two. The results were analysed using gravimetric as well as volumetric analysis. Alicona and Talysurf were employed for the surface topography, and scanning electron microscope was used to see the microstructural morphologies of the samples under different conditions. As a result, the electrochemical tests held at open circuit potential showed that, although DSS exhibited higher resistance to corrosion under seawater alone, NAB exhibited much higher resistance to corrosion when subjected to cavitation. From the experiments conducted, it was concluded that synergy had measurable impact on the cavitation erosion–corrosion of both NAB and DSS. NAB was found to be more susceptible to erosion under both the conditions as compared to DSS with prominent selective cavitation erosion of alpha phase in the microstructure. The overall synergism of NAB was found to be higher than that of DSS.

313. BATTEN, W.M.J., HARRISON, M.E. & BAHAJ, A.S.: "Accuracy of the actuator disc-RANS approach for predicting the performance and wake of tidal turbines", *Philosophical Transactions of the Royal Society Part A*, *vol. 371*, *issue. 1985*, DOI: 10.1098/rsta.2012.0293, 14-Jan-13
The actuator disc-RANS model has widely been used in wind and tidal energy to predict the wake of a horizontal axis turbine. The model is appropriate where large-scale effects of the turbine on a flow are of interest, for example, when considering environmental impacts, or arrays of devices. The accuracy of the model for modelling the wake of tidal stream turbines has not been demonstrated, and flow predictions presented in the literature for similar modelled scenarios vary significantly. This paper compares the results of the actuator disc-RANS model, where the turbine forces have been derived using a blade-element approach, to experimental data measured in the wake of a scaled turbine. It also compares the results with those of a simpler uniform actuator disc model. The comparisons show that the model is accurate and can predict up to 94 per cent of the variation in the experimental velocity data measured on the centreline of the wake, therefore demonstrating that the actuator disc-RANS model is an accurate approach for modelling a turbine wake, and a conservative approach to predict performance and loads. It can therefore be applied to similar scenarios with confidence.

314. BELMONT, M.R., CHRISTMAS, J. ,DANNENBERG, J., DUNCAN, J., DUNCAN, J.M. & FERRIER, B.: "An Examination of the Feasibility of Linear Deterministic Sea Wave Prediction in Multi-Directional Seas Using Wave Profiling Radar: Theory, Simulation and Sea Trials", *Journal of Atmospheric and Oceanic Technology*, *vol. 31*, *issue. 7*, pp. 1601-1614, DOI: 10.1175/JTECH-D-13-00170.1, Jul-14
For a number of maritime tasks there is a short time period, typically only a few tens of seconds, where a critical event occurs that defines a limiting wave height for the whole operation. Examples are the recovery of fixed and rotary winged aircraft, cargo transfers, final pipe mating in fluid transfer operations, and launch/recovery of small craft. The recovery of a 30-t rescue submersible onto a mother ship in the North Atlantic Treaty Organization (NATO) Submarine Rescue System is a prime example. In such applications short-term deterministic sea wave prediction (DSWP) can play a vital role in extending the sea states under which the system can be safely deployed. DSWP also has great potential in conducting experimental sea wave research at full scale. This report explores the feasibility of using data from an experimental wave profiling radar in achieving DSWP. The report includes theory, simulation, and field testing. Two forms of DSWP are employed: a fixed point system based upon a restricted set of wave directions from which some success is obtained and the other a fully two-dimensional technique that requires further development. The main finding is that using wave profiling radar for DSWP offers promise but requires improvements both to the spatial reliability and the resolution of the wave profiling radar and to the temporal resolution of its sweep before the technique can be considered to be viable as a usable tool.

315. BLACKMORE, T., GAURIER, B., MYERS, L., GERMAIN, G. & BAHAJ, A.S.: "The Effect of Freestream Turbulence on Tidal Turbines.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
The effects of steady state conditions (e.g. blade pitch, rotor yaw angle, blockage, velocity shear profile) on turbine performance has received much attention over the past few years. However, tidal flows are highly dynamic and their effects on turbine performance and reliability unknown. Previous work has shown how waves and uniform unsteady inflows increase the loadings acting on a turbine, but further investigation is required over a wider range of conditions. This work used static grids to generate turbulence with different turbulence intensities and length scales. Two different turbines were operated in these turbulent flows and their performance monitored and compared. It was found that increasing turbulence intensity reduces power and thrust coefficients by up to 10%,

and increases the fluctuations in thrust and torque. Increasing the turbulent length scale showed an increase in power and thrust coefficient, for each turbine, with a significant increase in their fluctuations. Overall, it has been found that turbulence has a significant effect on turbine performance and work is ongoing to consider a broader range of conditions with real site data.

316. BULL, S.J., MOHARRAMI, N., HAINSWORTH, S.V. & PAGE, T.F.: "The origins of chemomechanical effects in the low-load indentation hardness and tribology of ceramic materials.", *Special 50th Anniversary Issue, Journal of Material Science*, *vol. 51*, *issue. 1*, pp. 107-125, DOI: 10.1007/s10853-015-9412-3, Jan-16
We have used high-resolution techniques (nanoindentation, atomic force microscopy) to further isolate and identify environmental effects previously reported as possibly affecting both the microindentation response of a range of ceramic materials and their tribological behaviour. In order to make meaningful comparisons, these new experiments have been conducted alongside conventional Knoop and Vickers microhardness experiments conducted under identical conditions on the same samples. A range of polycrystalline, single crystal and amorphous ceramic materials have been studied including some only available as coatings. Our results show that thin adsorbate-modified layers (of dimensions ~1 nm) are almost invariably present on all the materials studied but their presence is not directly identifiable even by nanoindentation in most cases even if it does affect friction response. However, in crystalline materials, [(101¯2)(101¯2) sapphire and ZnO], we have been able to distinguish a further softening effect seen as a thicker layer (tens of nm) and believed associated with an adsorption-induced near-surface band-structure change affecting the motion of charged dislocations. This produces a measurable softening that is clearly evident in nanoindentation tests but less clear in microindentation tests. Finally, we present conclusions on the suitability of indentation testing for studying these phenomena, together with the implications of chemomechanical effects for influencing tribological performance and, thus, materials selection.

317. CRADDEN, L., SYRDA, P., RIORDAN, C. & INGRAM, D.: "Accessibility Risk for Offshore Platforms During Maintenance", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
There may exist a trade-off between the capacity for successful power production at a site, and the likelihood of having sufficiently frequent calm wind and wave conditions to allow safe access for maintenance. When assessing a site's suitability for installation of offshore renewable generation, the risk of non-completion of maintenance activities due to inaccessibility, and the impact of the potential inactive 'waiting' time must be factored into the decision criteria. In this study, suitable sites were selected for analysis and data extracted from a ten-year hindcast providing concurrent, collocated hourly wind and wave conditions. The fraction of hours accessible in each month was calculated, along with average window duration and waiting time. Both occurrence and persistence of conditions were found to be seasonally variable, with significant interannual variability at all sites. Joint probability distributions of wind and wave conditions were generated from the data, and additionally the probability of having suitable window durations. It is shown that the risk of being unable to complete activities with varying vessel thresholds and access times is relatively high in all cases. Comparing the different sites, a higher significant wave height appears to be more prohibitive than a higher wind speed.

318. ELASHA, F., MBA, D. & AMARAL TEIXEIRA, J.: "Condition monitoring philosophy for tidal turbines", *International Journal of Performability Engineering*, *vol. 10*, *issue. 5*, pp. 521, 2014
Renewable energy is currently considered as the main solution to reduce greenhouse gas emission. This has led to great developments in the use of renewable energy for electricity generation. Among many renewable energy resources, tidal energy has the advantage of being predictable, particularly when compared to wind energy. Currently the UK is the world leader in extracting energy from the tide; an estimation shows a potential of 67 TWh per year. In order to ensure safe operation and prolonged life for tidal turbines, condition monitoring is essential. The technology for power generation using tidal turbines is new therefore the condition monitoring concept for these devices is yet to be established. Also, there is a lack of understanding of techniques suitable for health monitoring of the turbine components and support structure given their unique operating environment. In this paper the condition monitoring of a tidal turbine is investigated. The objective is to highlight the need for condition monitoring and establish procedures to decide the condition monitoring techniques required, in addition to highlighting the impact and benefits of applying condition based maintenance. A model for failure analysis is developed to assess the needs for condition monitoring and identify critical components, after which a 'symptoms analysis' was performed to decide the appropriate condition monitoring techniques. Finally, the impact of condition monitoring on system reliability is considered.

319. FROST, C.A., TATUM, S., O'DOHERTY, T., MASON-JONES, A., MORRIS, C.E. & O'DOHERTY, D.M.: "Modelling tidal stream turbines", *13th World Renewable Energy Conference, London, UK.*, 3-8 Aug 2014
The transient behaviour of the sea and the rotation of a turbine rotor can result in high asymmetric loadings, which are transmitted to the drive shaft. A turbine mounted on a circular stanchion has been used to highlight the effects of introducing more realistic boundary conditions, over a rotational cycle of the turbine. The consequences on the turbine's performance characteristics and crucial structural loading are shown. The position of the turbine

relative to the support structure and its alignment to the flow direction can have significant temporal hydrodynamic and structural effects. Depending on their wavelength, waves can also have a significant effect on the overall design decisions and placement of devices. Thrust loading and bending moments applied to the drive shaft can be of the order of hundreds of kN and kNm, respectively. This leads to the need to not only size the drive shaft and bearings to account for axisymmetric thrust but also consider large asymmetric loads. Knowledge of the flow regime can allow the designers to evaluate material selection for components (i.e. for blades, etc.) and incorporate some deformation capability of the turbine blades to increase the power output and potentially alleviate some of the stress distribution through key structural points, that is, drive shaft, bearing connectors, etc. The resulting data can then be used to estimate component life via fatigue prediction. This chapter includes a multi-physics approach to modelling tidal energy devices and the potential for modelling to inform device condition monitoring.

320. GEBRESLASSIE, M.G., TABOR, G.R. & BELMONT, M.R.: "Investigating the Flow Conditions and Wake Interactions of Momentum-Reversal-Lift Tidal Turbine Using CFD", *Renewable Energy book section*, 2014
Interest in tidal energy exploitation has increased in recent years. One key factor in the exploitation of tidal energy is the development of efficient tidal turbines. This paper investigates the flow features and energy extrac-tion by a new type of tidal turbine design, the Momentum Reversal Lift (MRL), developed by AquaScientific Ltd using Computational Fluid Dy-namics (CFD), using a novel Immersed Body Force (IBF) turbine model-ing technique implemented within the open source CFD code OpenFOAM. The results from this modeling technique show complex flows within the turbine region and a downstream wake structure which reflects more closely that of the real turbines than simple momentum sink zone models such as the Actuator disc. It is also computationally cheaper than more detailed modeling techniques and can be easily used to model clusters of devices. The flow analysis shows faster wake recovery at high-er body forces. The performance of downstream devices was heavily in-fluenced by the wake interaction from the upstream turbine with short stream-wise turbine spacing, which indicates that proper optimization of the location of the devices is required in order to maximize the power ex-traction by individual devices in a tidal stream farm.

321. GONABADI, H.I., MOHARRAMI, N., OILA, A. & BULL, S.J.: "Predicting mechanical behaviour of tidal turbine blade made of composite materials using finite element code (ANSYS).", *ISSC18 2015 Conference, Lisbon, Portugal*, 15-18 June 2015
Fiber reinforced polymer (GFRP) composites are frequently used in the design of tidal turbine blades where composites are subjected to fatigue loads, however limited information is available to predict material behavior under coupled environmental and cyclic loading. This problem is addressed in this paper, by introducing a methodology for prediction of the fatigue behavior of composite tidal turbine blades. The methodology combines: (a) a finite element structural model for prediction of blade fatigue life and (b) performing cyclic tests at the material scale in sea water to generate realistic mechanical data for modelling. For simplicity reasons and regarding the typical loading on a tidal turbine blade, among different types of standard tests, three point bending fatigue tests (3PBT) were performed on GFRP composites. Finite element analyses (FEA) were then carried out to determine the stress distributions in a test specimen in static tests. This was used to predict failure of the composite and to interpret the experimental results of the specimens under static loads. To ensure the fatigue failure criterion is reasonable the fatigue failure mechanisms in specimens were investigated via microscopic techniques and it was found that inter-laminar cracks, delamination and breakage of fibers dominate the fatigue failure.

322. GONABADI, H.I., MOHARRAMI, N., OILA, A. & BULL, S.J.: "Wet flexural fatigue behaviour of tidal turbine blade composite materials", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Interest in tidal power is continuously increasing due to its huge potential for reliable renewable energy generation. This has led to the emergence of tidal turbine designs often inspired from earlier developments in the wind turbine industry. Composite materials including Glass fibre reinforced polymers (GFRP) are a low-cost, low weight and corrosion resistant material for this application. Cyclic loading due to tidal flow and wave conditions is a common characteristic of tidal turbine devices and the good fatigue performance of composite materials means they are widely used, however limited information are available to predict material behaviour under coupled environmental and cyclic loading. This problem is addressed in this paper, by introducing a methodology for prediction of the fatigue behaviour of composite tidal turbine blades. The methodology combines: (a) a hydrodynamic model for calculation of distributions of fluid–blade forces; (b) a finite element structural model for prediction of mechanical and fatigue behaviour of blade and (c) performing cyclic and quasi static tests at the material scale in the environment of sea water to generate realistic data for modelling. To ensure the fatigue failure criterion is reasonable the fatigue failure mechanisms in test samples were investigated via microscopic techniques and it was found that inter-laminar cracks, delamination and breakage of fibres that run through the thickness direction of composites dominate the fatigue failure.

323. GONABADI, H.I., MOHARRAMI, N., OILA, A. & BULL, S.J.: "Flexural characteristics of tidal turbine blades made of composite materials", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Predicting the mechanical performance of tidal turbine blades composed of different types of composites is considered. For simplicity reasons and regarding the typical loading on a tidal turbine blade, among different types of standard tests, static three point bending tests (3PBT) were performed on two different types of composites; fibre reinforced epoxy resins (FRP) and sandwich composite structures (CSM). 3- D finite element analyses (FEA) were then carried out to determine the stress distributions in a test sample in bending. This was used to predict failure of the composite, to interpret the experimental results and to interpret the failure modes of the test specimens. Mechanical behaviour of a full blade was analysed using the finite element method. Firstly loading on the blade is considered using computational fluid dynamics (CFD) and then mechanical testing results of each composite were used as input data in order to develop a simplified FEA so that static analysis could be performed with the ANSYS static structural analysis code to determine the critical zone on the blade where failure initiates. Mechanical behaviour of a blade made up of various composites is compared and the best composite from those tested for manufacturing of a tidal turbine blade is suggested.

324. GORDELIER, T., JOHANNING, L. & THIES, P.R.: "Reliability verification of mooring components for floating marine energy converters", *Ocean Renewable Energy, Energies Marines Renouvelables - EMR-2013, Brest, France*, 9-10 Oct 2013
Safety factors are critical to device reliability and are applied during device development to protect against early failures. At each stage of a development a designer may apply their own safety factor in relation to the criticality of the component or subassembly for which they are responsible. This paper seeks to understand how different assessment techniques can assist the design process by refining safety factors, with the aim of reducing device costs and improving economic viability. To achieve this, a methodology is presented to assess and verify the fatigue performance of mooring components. The paper draws on field data and introduces a combined approach of modelling, service simulation and field tests to validate the reliability of components. A shackle is used as a case study to demonstrate the methodology. Results from finite element analysis (FEA) and accelerated service simulation testing on the Dynamic Marine Component test facility (DMaC) are presented and discussed, including fatigue damage and failures. FEA is found to accurately predict areas of weakness within a component, however it underestimates component strength due to unrealistic stress concentrations at applied boundary conditions. Static and fatigue tests demonstrate the complex nature of reliability estimation, with static component safety factors of 8.6 being reduced to less than 3.7 under a fatigue loading regime. Service simulation testing is found to be important in refining initial reliability estimations from S-N curves and FEA models. The effect of mean stress on fatigue failure is also found to be significant.

325. GORDELIER, T., JOHANNING, L. &THIES, P.R.: "Component Reliability for Wave Energy Converters.", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
The reliability of marine renewable energy (MRE) converters is a key issue that has to be addressed and included in a whole system approach, in order to make the energy extraction from these sources a viable option. At the current development stage of MRE converters, an increasing number of devices are being field tested at pre-commercial demonstration scale, yielding field experience and load data useful for refining, demonstrating and improving the reliability of devices. This paper gives a brief review of the most advanced technologies and common reliability aspects that provide the rationale for dedicated component testing. It describes a service simulation test approach and the development of a unique large-scale component test facility. The test rig is capable of replicating the forces and motions experienced by components for a range of floating marine applications. The replication of motion angles is demonstrated in this paper. The service simulation test of a marine power cable is presented as a case study on how component performance can be assessed and demonstrated prior to long-term field deployments in order to ensure the reliability of crucial sub-systems and components in the harsh marine environment.

326. HARNOIS, V., SMITH, H., BENJAMINS, S. & JOHANNING, L.: "Assessment of entanglement risk to marine megafauna due to offshore renewable energy mooring systems", *International Journal of Marine Energy (IJME)*, *vol. 11*, pp. 27–49, DOI: 10.1016/j.ijome.2015.04.001, Sep-15
This paper defines a methodology to compare different offshore renewable energy (ORE) mooring configurations in terms of the risk of entanglement they present to marine megafauna. Currently, the entanglement of large marine animals is not explicitly considered in environmental impact studies. Recommendations need to be developed, assessing the risk of entanglement of ORE mooring configurations at the beginning of their design process. Physical parameters of the mooring system affecting the relative risk of entanglement have been identified as tension characteristics, swept volume ratio and mooring line curvature. These have been investigated further through six different mooring configurations: catenary with chains only, catenary with chains and nylon ropes, catenary with chains and polyester ropes, taut, catenary with accessory buoys, taut with accessory buoys.

Results indicate that the taut configuration has the lowest relative risk of entanglement, while the highest relative risk occurs with catenary moorings with chains and nylon ropes or with catenary moorings with accessory buoys. However, the absolute risk of entanglement is found to be low, regardless of the mooring configuration. This methodology can also be applied to other mooring configurations, arrays or power cables.

327. HARNOIS, V., THIES, P., & JOHANNING, L.: "On Peak Mooring Loads and the Influence of Environmental Conditions for Marine Energy Converters", *Journal of Marine Science and Engineering*, *vol. 4*, *issue. 2*, pp. 29, DOI: 10.3390/jmse4020029, Aug-16
Mooring systems are among the most critical sub-systems for floating marine energy converters (MEC). In particular, the occurrence of peak mooring loads on MEC mooring systems must be carefully evaluated in order to ensure a robust and efficient mooring design. This understanding can be gained through long-term field test measurement campaigns, providing mooring and environmental data for a wide range of conditions. This paper draws on mooring tensions and environmental conditions that have been recorded (1) for several months during the demonstration of an MEC device and (2) over a period of 18 months at a mooring test facility. Both systems were installed in a shallow water depth (45 m and 30 m, respectively) using compliant multi-leg catenary mooring systems. A methodology has been developed to detect peak mooring loads and to relate them to the associated sea states for further investigation. Results indicate that peak mooring loads did not occur for the sea states on the external contour line of the measured sea states, but for the sea states inside the scatter diagram. This result is attributed to the short-term variability associated with the maximum mooring load for the given sea state parameters. During the identified sea states, MEC devices may not be in survival mode, and thus, the power take-off (PTO) and ancillary systems may be prone to damage. In addition, repeated high peak loads will significantly contribute to mooring line fatigue. Consequently, considering sea states inside the scatter diagram during the MEC mooring design potentially yields a more cost-effective mooring system. As such, the presented methodology contributes to the continuous development of specific MEC mooring systems.

328. HARNOIS, V., WELLER, S., JOHANNING, L., THIES, P.R., LE BOULLUEC, M., LE ROUX, D., SOULÉ, V. & OHANA, J.: "Numerical model validation for mooring systems: Method and application for wave energy converters.", *Renewable Energy*, *vol. 75*, pp. 869-887, DOI: 10.1016/j.renene.2014.10.063, 2015
The design of wave energy mooring systems is challenging: overdesign incurs a significant cost penalty, underdesign may lead to a premature failure and incorrect design could reduce the power production. Consequently, compliant mooring systems are being developed for wave energy applications. This paper presents tank test results for a scale model of the buoy and mooring used at the South West Mooring Test Facility (SWMTF), an offshore facility developed to conduct long-term sea trials for wave energy device moorings. A compliant three leg catenary mooring system using Nylon ropes in the water column is investigated. Preliminary static, quasi-static, decay, regular and irregular wave tests were conducted on the 1:5 scale model, using the Ifremer basin in Brest. A corresponding numerical model was developed with a time-domain mooring modelling tool, inputting hydrodynamic data from a radiation/diffraction potential modelling program. After the calibration of several hydrodynamic parameters, the numerical model demonstrated good agreement with the experiment. However, numerical results show large differences with the field test results, mainly because of unknowns in the anchor position. The methods and procedures presented will allow the effective validation of numerical models to enable the development of appropriate mooring systems in wave energy applications.

329. HERDUIN, M., BANFIELD, S., WELLER, S., THIES, P.R., JOHANNING, L.: "Abrasion process between a fibre mooring line and a corroded steel element during the transit and commissioning of a Marine Renewable Energy device", *Journal of Engineering Failure Analysis*, *vol. 60*, pp. 137–154, DOI: 10.1016/j.engfailanal.2015.11.037, Feb-16
The interaction between fibre rope and steel parts on vessels (fairlead and roller) is technically well understood but not commonly published in codes or practised by mariners. What appears to be a smooth steel surface to the naked eye can still be abrasive medium to synthetic mooring components. There are very few reports of external rope abrasion tests in the literature. The surface finish at the contact between the rope and the steel guide can cause damage and consequently prematurely degrade the exposed yarns of the rope and thus reduces the overall load bearing capacity of the rope. The standard ISO 18692 [1] recommends that prolonged cycling of a rope around rollers should be avoided, however it is specified that occasional bending and running over rollers are allowable. There are two guides to specify surface roughness. MEG 3 [2]states that steel fairleads should be polished to Ra 10, but in practise this may be difficult to achieve or obtain with carbon steel. The US Navy guide also states that the surface of steel should have better than 125 μi or 3.2 Ra [3]. The study presented here discusses the bending of a synthetic rope around a roller during transportation. It relates the motion behaviour of the vessel to rope wear and provides a detailed numerical simulation correlated with post analysis of the rope after the failure. The investigations show that the roughness of the steel roller caused the abrasion of the rope which was exacerbated through the vessel dynamics, resulting in the rope having an estimated residual strength of

14% MBL before rupture. The experimental tests have established a linear relation between strength loss and surface roughness and it was observed that the abrasion mainly occurs in the early stages of load cycling. The presented work recommends the use of lubricated nylon instead of carbon steel rollers to limit abrasive rope wear. The paper also devises a methodology to carefully assess and quantify potential rope abrasion to ensure that the residual rope strength withstands the required load capacity.

330. KARIKARI-BOATENG, K.A., NG, C., GRIMWADE, J., JOHANNING, L., MUELLER, M.A. & BARLTROP, N.: "Reliability of Tidal Turbines using Wind Turbine Experience", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
Reliability of an emerging technology is critical to the success of the technology. One of the emerging technologies for extracting offshore renewable and sustainable energy is the horizontal axis tidal current turbine. They are, in term of configuration and technology, very similar to medium size horizontal axis wind turbines. Due to their similarity it is possible and reasonable to use experience in the wind industry to investigate the potential reliability issues that may occur in the tidal industry. One of the persistent reliability issues in the wind industry is the failure of wind turbine drivetrains. Design deficiencies caused by a lack of in-depth understanding of the operating conditions had been suggested as the possible cause of failures. It is therefore critical that the operating conditions of tidal current turbines are thoroughly understood. Understanding and quantifying the loads will play an important role in assessing the reliability of tidal turbine designs. This paper demonstrates the influence of tidal turbulence on non-torque loads in the main shaft of a tidal turbine. Loads in the main shaft are transmitted through the drivetrain hence some common failure modes which may occur in the drivetrain are discussed.

331. MARSH, G., WIGNALL, C., THIES, P.R., BARLTROP, N., INCECIK, A., VENUGOPAL, V. & JOHANNING, L.: "Review and Application of Rainflow Residue Processing Techniques for Accurate Fatigue Damage Estimation", *International Journal of Fatigue, International Journal of Fatigue*, *vol. 82*, *issue. 3*, pp. 757–765, DOI: 10.1016/j.ijfatigue.2015.10.007, Jan-16
Most fatigue loaded structural components are subjected to variable amplitude loads which must be processed into a form that is compatible with design life calculations. Rainflow counting allows individual stress cycles to be identified where they form a closed stress–strain hysteresis loop within a random signal, but inevitably leaves a residue of open data points which must be post-processed. Comparison is made between conventional methods of processing the residue data points, which may be non-conservative, and a more versatile method, presented by Amzallag et al. (1994), which allows transition cycles to be processed accurately. This paper presents an analytical proof of the method presented by Amzallag et al. The impact of residue processing on fatigue calculations is demonstrated through the application and comparison of the different techniques in two case studies using long term, high resolution data sets. The most significance is found when the load process results in a slowly varying mean stress which is not fully accounted for by traditional Rainflow counting methods.

332. MARTA, M., MUELLER-SCHUETZE, S., OTTERSBERG, H., ISUS, D., JOHANNING, L. & THIES, P.R.: "Development of dynamic submarine MV power cable design solutions for floating offshore renewable energy applications", *Int. Conf. on Insulated Power Cables, Versailles, France*, 21-25 June 2015
This paper reviews approaches to design, modelling and testing of submarine dynamic power cables given the systems requirements for floating offshore renewable energy (ORE). It mainly focuses on the global loading regime and internal mechanical stress estimation in highly dynamic working conditions as well as the assessment of cable mechanical properties, strength and fatigue life.

333. MARTIN, R., LAZAKIS, I., BARBOUCHI, S. & JOHANNING, L.: "Initial Sensitivity Analysis of Offshore Wind Operations and Maintenance Cost and Availability", *Renewable Energy*, *vol. 85*, pp. 1226–1236, DOI: 10.1016/j.renene.2015.07.078, Jan-16
Operation and Maintenance (O&M) costs are estimated to account for 14%–30% of total Offshore Wind Farm (OWF) project lifecycle expenditure according to a range of studies. In this respect, identifying factors affecting operational costs and availability are vital for wind farm operators to achieve the most profitable decisions. Many OWFs are built in stages and the important factors may not be consistent for the different phases. To address this issue, three OWF case studies are defined to represent two phases and a complete project. An initial qualitative screening sensitivity analysis was conducted to identify the most important factors of O&M affecting operating cost and availability. The study concluded that the important factors for total O&M cost were access and repair costs along with failure rates for both minor and major repairs. For time-based availability, the important factors identified were those related to the length of time conducting the maintenance tasks, i.e. the operation duration and the working day length. It was found that the two stages had similar results, but these were different compared to the complete project. In this case, the results provide valuable information to OWF operators during the project development and decision making process.

334. MASON-JONES, A. ET AL.: "Influence of a velocity profile & support structure on tidal stream turbine performance", *Renewable Energy*, *vol. 52*, pp. 23-30, DOI: 10.1016/j.renene.2012.10.022, Apr-13
With tidal turbine technology in its infancy prototype devices are likely to be positioned at locations where both the local marine environment and vessel navigation are favourable. However, as marine turbine technology develops toward economic viability there is a propensity for undesirable interactions with local shipping, higher turbulence levels and velocity shear through the water column to occur. The latter high shear could result from positioning the turbine lower in the water column, perhaps due to local shipping requirements. This paper helps to elucidate the performance of the tidal turbine and in particular the blade forces during rotation within a high shear velocity profile. A velocity profile from ADCP measurements was used as an inlet boundary for CFD analysis. The work shows that the presence of a suitably positioned stanchion downstream of the turbine will result in reduced performance characteristics over a complete rotation. However, the amplitude of the characteristics, in particular, the axial loading increases which would require careful design considerations.

335. MASON-JONES, A., O'DOHERTY, D.M., MORRIS, C.E., O'DOHERTY, T., BYRNE, C.B., PRICKETT, P.W., GROSVENOR, R.I., OWEN, I., TEDDS, S. & POOLE, R.J.: "Non-dimensional scaling of tidal stream turbines", *Energy*, *vol. 44*, *issue. 1*, pp. 820-829, DOI: 10.1016/j.energy.2012.05.010, Aug-12
The impact of local depth-wise velocity profiles on tidal turbine performance is important. Although the use of standard power laws for predicting velocity profiles is common, these laws may underestimate the magnitude of the depth-wise velocity shear and power attenuation. Predicting the performance of a tidal turbine in a high velocity shear is crucial in terms of power extraction. This paper discusses the dimensional scaling of a turbine using CFD and experimental data. Key performance characteristics (power, torque and thrust coefficients) were studies with increasing diameters and velocities, by generating. a series of non-dimensional curves. This provides a first order approximation for matching turbine performance characteristics to site conditions. The paper also shows that the use of a volume-averaged velocity derived from the upstream velocity profile can be used to determine these key performance characteristics. These are within 2% of those determined assuming a uniform flow. The paper also shows that even changes in the blade pitch angle results in new turbine characteristics under uniform velocity conditions and it is expected that these can be used for profiled flow.

336. MASTERS, I., MALKI, R., WILLIAMS, A.J. & CROFT, T.N.: "A Modified k- ε Turbulence Model for Tidal Stream Turbine Modelling Using a Coupled BEM-CFD Model", *Fourth International Conference on Ocean Energy (ICOE), Dublin, Ireland*, 17-19 Oct 2012
The coupled Blade Element Momentum -Computational Fluid Dynamics (BEM-CFD) model offers a computationally efficient tool for simulating Tidal Stream Turbines (TSTs). The model is used to evaluate TST performance through simulations over a range of tip speed ratios and flow velocities. When compared to other modelling approaches, such as classical Blade Element Momentum Theory (BEMT) or pure CFD modelling, the coupled model has a tendency to over-predict rotor performance. When compared to CFD results with geometry defined blade surfaces, the model is computationally less expensive but under-predicts wake recovery. One possible reason for this is that the source terms used to represent the rotor are only introduced into the momentum equations of the CFD model, and not the turbulence equations. This paper will attempt to address this aspect by introducing an additional term to the dissipation rate equation of the standard k- ε turbulence model. The purpose of this term is to represent the breakdown of largescale turbulence to small-scale turbulence at the location of the blades. Variation in the value of this additional term with flow velocity and tip speed ratio of the rotor will be evaluated.

337. MCCOMBES, T., JOHNSTONE, C.M. & GRANT, A.D.: "Supergen Marine Research: Modelling Wave Induced Flow Effects on Tidal Turbines", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
At the present time there is growing requirement for greater understanding of wave current interactions and their influence on tidal turbines. Wave surge can result in heavy, fatigue inducing loads on turbine structures and turbulence generated at a free surface penetrates the water column interacting with the turbine flow-field with impacts on performance. While an increasing number of experimental results are available, there are few numerical tools specifically geared towards this task. This paper reports work on flow modelling and analysis software undertaken as part of the SUPERGEN, UK Centre for Marine Energy Research by Strathclyde University. Part of this work seeks to improve the ability to model wave induced turbulence efficiently, correctly and at various scales with a goal of using appropriate input data from real sea conditions to ensure representative turbulence velocity fields are captured accurately within numerical models. This paper describes two approaches to extending a numerical model to include wave effects in computations of a tidal turbine rotor – an engineering approach using a simple wave theory allowing fast analysis at the cost of physics, and using a Cartesian cut-cell approach to include additional effects allowing a higher resolution analysis.

338. MORRIS, C.E., MASON-JONES, A., O'DOHERTY, T. & O'DOHERTY, D.M.: "Marine turbine blade stiffness attenuation and its effect on kinetic energy extraction", *Renewable Energy*, *vol. 88*, pp. 30-39
The hydrodynamic forces imparted on a tidal turbine rotor, whilst causing it to rotate and hence generate power,

will also cause the blades to deform. This deformation will affect the turbine's performance if not included in the early design phase and could lead to a decrease in power output and a reduction in operational life. Conversely, designing blades to allow them to deform slightly may reduce localised stress and therefore prolong the life of the blades and allow the blades to deform in to their optimum operational state. The aim of this paper is to better understand the kinetic energy extraction by varying the material modulus of a turbine blade. Shaft torque/power, blade tip displacement, and axial thrust results are presented for 2, 3 and 4 bladed rotor configurations at peak power extraction. For the rotor design studied the FSI model data show that there is a low sensitivity to blade deformation for the 2, 3 and 4 bladed rotors. However, the results reveal that the 3 bladed rotor displayed maximum hydrodynamic performance as a rigid structure which then decreased as the blade deformed. The 2 and 4 bladed rotor configurations elucidated a slight increase in hydrodynamic performance with deflection.

339. ORDONEZ-SANCHEZ S., JOHNSTONE C. & GRANT A.: "Tow tank testing of tethered marine turbines to determine system dynamic response", *EWTEC 2011, Southampton, UK*, Sep-11
The installation and maintenance of marine energy converters is substantially complicated in deep water locations. From the experiences of the oil industry, flexible moorings might be an economic and effective solution. A major advantage when used with tidal turbines is that they self-align with the flow, making it possible to simplify control techniques while lowering the cost of the system and minimizing the surface piercing visual impact. To ensure stability and structural integrity, such systems would require a thorough analysis of dynamic response in all anticipated sea states. The focus of this paper is thus the study of several kinds of flexible moored devices; co-axial contra rotating, in-plane counter rotating and single rotor systems. Several model devices, all of 0.3 m rotor diameter, were tested over a range of relative velocities in a tow tank at Strathclyde University. All rotors were designed with detachable blades to facilitate a study of the effect of blade pitch angle on performance. An accelerometer to measure roll, pitch and yaw for the complete device was installed on each. Strain gauges were adapted to measure the torque of each rotor configuration and the corresponding thrust. A submersible camera was used to estimate the angular velocity of each rotor. The results of the tests demonstrate the advantages and disadvantages of the devices in the same conditions, thus, the convenience of each of them in diverse situations is highlighted.

340. RANSLEY, E., BROWN, S., GREAVES, D., HINDLEY, S., WESTON, P., GUERRINI, E. & STARZMANN, R.: "Coupled RANS-VOF Modelling of Floating Tidal Stream Concepts", *Proceedings of the 4th Marine Energy Technology Symposium (METS), Washington, D.C., USA*, 25-27 April 2016
Numerical models are now capable of providing the quantitative description required for engineering analysis. However, for structures such as floating tidal stream devices, the complex nature of the system can rarely be included using the existing functionality of such models. In this article, a coupled Computational Fluid Dynamics (CFD) model, based on OpenFOAM®, is presented. The model includes: waves and currents derived from environmental conditions at the Perpetuus Tidal Energy Centre (PTEC) site; fully nonlinear, two-phase fluid dynamics solved via the Reynolds-Averaged Navier-Stokes (RANS) equations using the Volume Of Fluid (VOF) method; a floating structure with full six degrees of freedom rigid–body motion; a 4-point nonlinear hybrid-catenary mooring system, and; a new two-way coupled actuator disc-type turbine model based on a 4m diameter Schottel Instream Turbine (SIT). Simulations have been performed at full scale for a device with and without the turbine installed; in 6.1m, 9s waves and peak spring tidal currents (surface flow velocity of ~2.8m/s), both separately and simultaneously. It has been shown that the motion, mooring loads and power output of the device, display considerable complexities beyond simple periodic behaviour. It is clear that, both currents and waves need to be considered simultaneously and that the key elements of these systems are strongly coupled. Consequently coupled models, such as the one proposed here, including the complete device system and full range of hydrodynamic conditions, are required to understand the behaviour and power delivery of floating tidal stream concepts.

341. RINALDI, G., JOHANNING, L., THIES, P. R., & WALKER, R. T.: "Comparison of offshore renewable technologies using a reliability-based simulation tool.", *2nd International Conference on Renewable Energies. Lisbon, Portugal.*, 24-Oct-16
The Operation and maintenance (O&M) of offshore renewables has been highlighted as one of the most difficult aspects to evaluate for the viability of marine energy farms. In this work the authors compare two case studies, with particular regard to reliability and availability improvement, examining two of the most significant categories in offshore energy conversion: offshore wind and wave energy converters. A new decision support model for simulating the operating life of marine renewables is presented. Results provided in terms of costs, reliability, energy production and availability are analysed and compared for two simulated offshore farms composed of offshore wind turbines and wave energy converters respectively. The ultimate aim of the paper is to show the type of information the developed O&M simulation tool can supply in order to assist farm owners and operators in the decision-making process of cost reduction related to the deployment of marine energy farms.

342. RODRIGUEZ, A., WELLER, S.D., CANEDO, J., RODRIGUEZ, R., GONZALEZ DE LENA, V., THIES, P.R., PARISH, D., JOHANNING, L. & LEAO, A.: "Performance Comparison of Marine Renewable Energy Converter Mooring Lines Subjected to Real Sea and Accelerated Loads.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
One immediate challenge for the commercial development of floating Marine Renewable Energy Converters is reducing the weight and associated costs of mooring lines in deep water (>75m). Synthetic fibre ropes offer already a solution to the weight problems of using steel lines in deep-water offshore oil and gas installations as they have a very low weight in water. The present study focuses on the performance of fibre ropes in shallow waters, subjected to real sea conditions and the replication of the same loads accelerated in time. Determining fatigue life is one of the most important aspects of long-term mooring analysis. At present, the fatigue analyses are usually based on S-N or T-N curves that are obtained with regular loads even when these loads are completely different to the ones measured at sea by a wave energy converter. The differences between the standard fatigue test and the real life of a mooring system are mainly the rate in which the loads are applied and the profile of the loads. Here, these two elements are analysed to get the fatigue damage, obtaining important differences in this measure.

343. SHARIFI, S., JOHNSTONE, C. & STACK, M.M.: "Tribological challenges of scaling up tidal turbine blades.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Generating electricity from renewable resources (wind, wave and tidal) is of increasing interest. Of all marine renewables, tidal energy, by comparison, possesses the higher persistency and predictability over long time scales and the higher density of water than air results in greater power output from a tidal turbine than a wind turbine with similar dimensions. However, due to the nature of the tides, developing a reliable device for such environments, especially with an increased rotor diameter, raises more challenges to be addressed including the tribological challenges such as sediment erosion, cavitation erosion and their possible synergistic effects on the tidal turbine blades. This research focuses on testing and developing materials for improved tribological performance in tidal environments. This includes producing a variety of composite materials with different fibres and layouts reinforcement to evaluate two main tribological issues of composite materials in tidal environments: matrix cutting and reinforcement fracture using a loped test rig, which measures the effects of impact angle, particle size and concentrations at different tip speeds. The test samples are analysed using scanning electron microscopy (SEM) to conduct a surface topography and characterisation.

344. STRATIGAKI, V., TROCH, P., STALLARD, T., FOREHAND, D., FOLLEY, M., KOFOED, J.P., BABARIT, A. & BENOIT, M.: "Modelling of wave attenuation induced by multi-purpose floating structures.", *34th International conference on Coastal Engineering, ASCE, Seoul, Korea*, 15-20 June 2014
Experiments have been performed in the Shallow Water Wave Basin of DHI (Hørsholm, Denmark) within the EU FP7 Hydralab Programme, on large farms of up to 25 heaving point absorber type Wave Energy Converters (WECs). For a range of geometric lay-out configurations and wave conditions (regular, polychromatic, long- and short-crested irregular waves), WEC response and modification of the wave field have been measured to provide data for the understanding of WEC farm interactions and for the evaluation of farm interaction numerical models. A first extensive wave farm database is established. The experimental arrangement and the obtained database are presented, as well as results for wave height attenuation downwave of the farms. For long-crested irregular waves, up to 18.1 % and 20.8 % reduction in significant wave height is observed downwave of the 5x5-WEC rectilinear and staggered farm, respectively. Wave height attenuation is expected to be larger, since in practical wave farm applications WECs will be controlled to extract a large amount of power from the waves, and therefore the array will cause larger wave height dissipation. These findings present the ability to combine the harvesting of energy from sea waves with coastal defence systems, resulting in cost reduction for both applications when WECs operate as multi-purpose devices.

345. TEDDS, S.C., DE JESUS HENRIQUES, T.A., WHALLEY, R.D., OWEN, I. & POOLE, R.J.: "A cautionary note when using Acoustic Doppler Velocimetry for turbulence measurements for marine energy applications", *International Journal of Marine Energy*, 2014
Acoustic Doppler Velocimeters (ADVs) have been a key research tool in marine energy. This study investigates the issues in using ADVs for turbulence measurements. An ADV in different orientations is used to measure the mean and standard deviations of three dimensional velocities in a channel flow with uniform and in a shear flow downstream of a tidal turbine. In different probe orientations the mean velocities measured by the ADV agree however there are differences in the standard deviations of the velocities. Velocity measurements were taken simultaneously using a 1D Laser Doppler Velocimeter (LDV) and ADV. Results for streamwise and vertical velocities are compared and it is found that the ADV does well in matching the means and one of the standard deviations of the velocity components, but the ADV overestimates the other two components. This ‘noise’ is not constant and changes for different turbulence levels, thus there is no simple solution to remove it. It is therefore important to consider that the standard deviations measured by the ADV contain ‘noise’ depending on the probe orientation.

346. THIES, P.R., CROWLEY, S., JOHANNING, L., MICKLETHWAITE, W., YE, H., TANG, D., CUI, L. & LI, X.: "Novel mooring design options for high-intensity typhoon conditions – an investigation for wave energy in China.", *The Royal Institution of Naval Architects - Structural Load & Fatigue on Floating Structures, London, United Kingdom*, 25-26 February 2015
The industrialised and densely populated coastal regions in China are in search of local energy supplies in order to avoid expensive energy transmission from the West of China. Wave energy technology is considered as one of the possible solutions with a potential installed capacity of 13GW around China. However, typhoons are a major meteorological threat for China's coastal regions with estimated damages of over 20bnRMB. Prediction, prevention and mitigation of typhoons have greatly improved and coastal regions at risk are readily identified. This paper will outline the environmental load conditions that are faced by floating installations in the Chinese Sea. The paper assesses the feasibility of novel mooring solutions that aim to absorb energy during the most severe load conditions in order to reduce peak and fatigue loads. Their suitability for wave energy converters in high-intensity typhoon conditions is assessed by a fully-coupled hydrodynamic analysis. Initial modelling has been conducted in the time-domain employing a moored cylindrical buoy with six degrees of freedom. The mooring line properties have been chosen to be characteristic of the strongly nonlinear behaviour of novel mooring designs. The results show a reduction in peak loads along the entire length of the mooring line in comparison to standard rope mooring, whilst crucially not restricting the heave motion of the buoy. These initial results will inform the refinement and optimisation of the mooring design of floating installations for high-intensity typhoon conditions.

347. THIES, P.R., JOHANNING, L. & GORDELIER, T.: "Component reliability testing for wave energy converters: Rationale and implementation", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
The reliability of marine renewable energy (MRE) converters is a key issue that has to be addressed and included in a whole system approach, in order to make the energy extraction from these sources a viable option. At the current development stage of MRE converters, an increasing number of devices are being field tested at pre-commercial demonstration scale, yielding field experience and load data useful for refining, demonstrating and improving the reliability of devices. This paper gives a brief review of the most advanced technologies and common reliability aspects that provide the rationale for dedicated component testing. It describes a service simulation test approach and the development of a unique large-scale component test facility. The test rig is capable of replicating the forces and motions experienced by components for a range of floating marine applications. The replication of motion angles is demonstrated in this paper. The service simulation test of a marine power cable is presented as a case study on how component performance can be assessed and demonstrated prior to long-term field deployments in order to ensure the reliability of crucial sub-systems and components in the harsh marine environment.

348. THIES, P.R., JOHANNING, L. & SMITH, G.H.: "Lifecycle fatigue load spectrum estimation for mooring lines of a floating marine energy converter", *31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Rio De Janeiro, Brazil*, 1-6 July 2012
One of the key engineering challenges for the installation of floating marine energy converters is the fatigue of the load-bearing components. In particular the moorings which warrant the station-keeping of such devices are subject to highly cyclic, non-linear load conditions, mainly induced by the incident waves. To ensure the integrity of the mooring system the lifecycle fatigue spectrum must be predicted in order to compare the expected fatigue damage against the design limits. The fatigue design of components is commonly assessed through numerical modelling of representative load cases. However, for new applications such as floating marine energy converters numerical models are often scantily validated. This paper describes an experimental approach, where load measurements from tank tests are used to estimate the lifecycle fatigue load spectrum for a potential deployment site. The described procedure employs the commonly used Rainflow cycle analysis in conjunction with the Palmgren-Miner rule to estimate the accumulated damage for individual sea states, typical operational years and different design lives. This allows the fatigue assessment of mooring lines at a relatively early design stage, where both information from initial tank tests and the wave climate of potential field sites are available and can be used to optimise the mooring design regarding its lifecycle fatigue conditions.

349. THIES, P.R., JOHANNING, L. & SMITH, G.H.: "Assessing mechanical loading regimes and fatigue life of marine power cables in marine energy applications", *Journal of Risk and Reliability*, *vol. 226*, *issue. 1*, pp. 18-32, DOI: 10.1177/1748006X11413533, Feb-12
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 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.

350. THIES, P.R., JOHANNING, L., HARNOIS, V., SMITH, H.C.M. & PARISH, D.N.: "Mooring line fatigue damage evaluation for floating marine energy converters: Field measurements and prediction.", *Renewable Energy*, *vol. 63*, pp. 133-144, DOI: 10.1016/j.renene.2013.08.050, Mar-14
The vision of large-scale commercial arrays of floating marine energy converters (MECs) necessitates the robust, yet cost-effective engineering of devices. Given the continuous environmental loading, fatigue has been identified as one of the key engineering challenges. In particular the mooring system which warrants the station-keeping of such devices is subject to highly cyclic, non-linear load conditions, mainly induced by the incident waves.To ensure the integrity of the mooring system the lifecycle fatigue spectrum must be predicted in order to compare the expected fatigue damage against the design limits. The fatigue design of components is commonly assessed through numerical modelling of representative load cases. However, for new applications such as floating marine energy converters numerical models are often scantily validated.This paper describes an approach where load measurements from large-scale field trials at the South West Mooring Testing Facility (SWMTF) are used to calculate and predict the fatigue damage. The described procedure employs a Rainflow cycle analysis in conjunction with the Pålmgren–Miner rule to estimate the accumulated damage for the deployment periods and individual sea states.This approach allows an accurate fatigue assessment and prediction of mooring lines at a design stage, where field trial load measurements and wave climate information of potential installation sites are available. The mooring design can thus be optimised regarding its fatigue life and costly safety factors can be reduced. The proposed method also assists in monitoring and assessing the fatigue life during deployment periods.

351. THIES, P.R., JOHANNING, L., KARIKARI-BOATENG, K.A., NG, C. & MCKEEVER, P.: "Component reliability test approaches for marine renewable energy", *Proc IMechE Part O: J Risk and Reliability, Spec. Iss. Offshore Renewable Energy*, *vol. 229*, *issue. 5*, pp. 403-416, DOI: 10.1177/1748006X15580837, Apr-15
An increasing number of marine renewable energy (MRE) systems are reaching the stage where a working prototype must be demonstrated in operation in order to progress to the next stage of commercial projects. This stage is often referred to as 'valley of death' where device developers face the challenge of raising capital needed to demonstrate the prototype. The dilemma is that investors understandably demand a proven track record and demonstrated reliability in order to provide capital. One way to resolve this dilemma is specific component reliability testing that not only satisfies investor expectations but holds the potential to improve and de-risk components for MRE. This paper gives an overview to different component reliability test approaches in established industries and for MRE, covering both wave and tidal energy technologies. There has been notable activity in the research community to develop and implement dedicated component reliability test rigs that allow the investigation and demonstration of component reliability under controlled, yet representative conditions. Two case studies of physical test rigs will illustrate the possible test approaches. The Nautilus Powertrain test rig, a facility at the Offshore Renewable Energy (ORE) Catapult, focuses on the demonstration and testing of drive train components including gearboxes, generators, mechanical couplings and bearings. The Dynamic Marine Component test rig (DMaC) at the University of Exeter aims to replicate the forces and motions for floating offshore applications and their subsystems, including mooring lines and power cables. This paper highlights the relevance of component testing and qualification prior to large-scale commercial deployments and gives an insight to some of the test capabilities available in the sector. Several case studies illustrate the component test approach for tidal energy (Nautilus) and wave energy (DMaC) applications.

352. THIES, P.R., SMITH, G.H. & JOHANNING, L.: "Addressing failure rate uncertainties of marine energy converters", *Renewable Energy*, *vol. 44*, pp. 359-367, DOI: 10.1016/j.renene.2012.02.007, Aug-12
The interest in marine renewable energy is strong, but has not led to significant commercial-scale investment and deployment, yet. To attract investors and promote the development of a marine renewable industry a clear concept of project risk is paramount, in particular issues relating to device reliability are critical. In the public domain, reliability information is often scarce or inappropriate at this early stage of development, as little operational experience has been gained. Thus, reliability estimates are fraught with large uncertainties. This paper explores sources and magnitudes of failure rate uncertainty and demonstrates the effect on reliability estimates for a notional marine energy converter. If generic failure rate data forms the basis of a reliability assessment, reliability estimates are not robust and may significantly over- or underestimate system reliability. The Bayesian statistical framework provides a method to overcome this issue. Generic data can be updated with more specific

information that could not be statistically incorporated otherwise. It is proposed that adopting such an approach at an early stage in an iterative process will lead to an improved rate of certainty.

353. THIES, P.R., TUK, T., TUK, M., MARTA, M., MUELLER-SCHUETZE, S. & JOHANNING, L.: "Accelerated reliability testing of articulated cable bend restrictor in floating marine energy applications", *International Journal of Marine Energy (IJOME)*, DOI: 10.1016/j.ijome.2016.05.006, 2016
Power cable failures for offshore marine energy applications are a growing concern since experience from offshore wind has shown repeated failures of inter-array and export cables. These failures may be mitigated by dedicated cable protection systems, such as bend restrictors. This paper presents the rationale and the results for accelerated reliability tests of an articulated bend restrictor. The tests are a collaborative effort between the University of Exeter, CPNL Engineering and NSW, supported by the EU MARINET programme. The tests have been carried out at full-scale and exposed the static submarine power cable, fitted with an articulated pipe bend restrictor, to mechanical load regimes exceeding the allowable design loads in order to provoke accelerated wear and component failures. The tested load cases combined cyclic bending motions with oscillating tensile forces. A range of acceleration factors have been applied in respect to the 1:50 years load case, subjecting each of the three restrictor samples to 25,000 bending cycles (50,000 tensile cycles). The static power cable was also loaded beyond its intended use, testing the worst case scenario of repeated dynamic loading, purposely inflicting failure modes for investigation. Throughout the test the static submarine power cable sustained over 77,000 bending cycles. The test demonstrated the integrity of the cable protection system with quantified wear rates obtained through 3D scanning of the individual shells. The static power cable also maintained its integrity throughout the accelerated test regime. None of the failure modes, mainly fatigue cracks and fretting of individual wires, identified by cable dissection would have caused a direct loss of service. The observed failure modes could also be predicted through numerical load analysis, giving confidence in the utilised mechanical modelling and cross-sectional analysis for dynamic applications.

354. WALSH, J., BASHIR, I., THIES, P.R., BLONDEL, P. & JOHANNING, L.: "Acoustic Emission Health Monitoring of Marine Renewables - Illustration with a Wave Energy Converter in Falmouth Bay (UK)", *PRIMaRE Conference, Penryn, United Kingdom*, 16-Jun-15
Marine renewable energy (MRE) is an emerging technology and at present there are an increasing number of MRE prototypes and full-scale devices deployed. The future commercialization in the near future may contribute to the mitigation of carbon emissions and diversify the renewable electricity generation portfolio. Because of the high costs of marine intervention, it is important to establish reliable, remote monitoring techniques. The underwater sound around MRE devices is often monitored for environmental impact assessments. This approach can also be potentially utilized to monitor the engineering health of MRE devices. This is the objective of the project ÆMORE (Acoustic Emission technology for environmental and engineering health Monitoring of Offshore Renewable Energy), jointly conducted by the Universities of Exeter and Bath, with J+S Ltd. Acoustic Emission (AE) monitoring is already used for Structural Health Monitoring (SHM) of land-based structures and devices such as wind turbines. AE allows faults and defects to be detected early in a device's lifetime, providing more time to plan and implement necessary maintenance and repair procedures to avoid catastrophic failure. This is highly desirable for MRE structures, which operate in energetic seas with tight weather access windows. This paper explores the remit for AE monitoring to SHM and maintenance planning for MRE devices and demonstrates that this novel application is principally feasible. A brief review of the state of the art of AE for land-based systems aids to illustrate how its techniques can be applied to underwater environments and MRE components. This literature review will inform a classification system that relates likely failure modes to their expected acoustic emissions. The results from previous underwater environmental studies are used to evaluate their potential for SHM of MRE structures. AE environmental data collected during the operation of the Fred Olsen Lifesaver wave energy - onverter at the Falmouth Bay Test site (FaBTest, SW UK) is used to demonstrate this novel application. The case study provides proof that this concept is valid for underwater SHM of marine renewable structures.

355. WELLER, S., THIES, P.R., GORDELIER, T. & JOHANNING, L.: "Reducing Reliability Uncertainties for Marine Renewable Energy", *Journal of Marine Science and Engineering (JMSE), Special Issue "ASRANet - Offshore Renewable Energy"*, *vol. 3:1349-1361*, DOI: 10.3390/jmse3041349, 05-Nov-15
Technology Readiness Levels (TRLs) are a widely used metric of technology maturity and risk for marine renewable energy (MRE) devices. To-date, a large number of device concepts have been proposed which have reached the early validation stages of development (TRLs 1–3). Only a handful of mature designs have attained pre-commercial development status following prototype sea trials (TRLs 7–8). In order to navigate through the aptly named “valley of death” (TRLs 4–6) towards commercial realisation, it is necessary for new technologies to be de-risked in terms of component durability and reliability. In this paper the scope of the reliability assessment module of the DTOcean Design Tool is outlined including aspects of Tool integration, data provision and how prediction uncertainties are accounted for. In addition, two case studies are reported of mooring component fatigue testing

providing insight into long-term component use and system design for MRE devices. The case studies are used to highlight how test data could be utilised to improve the prediction capabilities of statistical reliability assessment approaches, such as the bottom–up statistical method.

356. WELLER, S.D., DAVIES, P., VICKERS, A.W. & JOHANNING, L.: "Synthetic Rope Responses in the Context of Load History: The Influence of Aging.", *Ocean Engineering*, *vol. 69*, pp. 192-204, DOI: 10.1016/j.oceaneng.2014.12.013, 2015
In order to design marine renewable energy mooring systems which are both economical and durable it is necessary to establish the lifecycle performance of individual components. In parallel with numerical tool development, physical component testing utilising realistic load cases is pivotal in achieving a greater understanding of performance variations including the contribution of degradation mechanisms. Building upon previous experimental tests conducted by the authors, tension–tension tests were conducted on a sample used in first part of the study and samples extracted from a mooring line which was deployed for 18 months with the South West Mooring Test Facility. In agreement with the first part of the study it was found that sample axial stiffness and damping are influenced by load history and instantaneous strain. The increased compliance, lower load bearing capacity and reduced tension–tension fatigue performance of aged specimens are symptomatic of fibre-on-fibre abrasion damage sustained in service. Visual inspections of the rope and yarns including scanning electron microscope analysis of fibres revealed that abrasion wear was accelerated by debris found within the rope structure, highlighting the importance of preventing particle ingress. Datasets are provided to facilitate the development of rope and mooring system simulation tools.

357. WELLER, S.D., JOHANNING, L., DAVIES, P. & BANFIELD, S.J.: "Synthetic Mooring Ropes for Marine Renewable Energy Applications", *Renewable Energy*, *vol. 83*, pp. 1268–1278, DOI: 10.1016/j.renene.2015.03.058, May-15
Synthetic mooring ropes have a proven track record of use in harsh operating conditions over the past two decades. As one of the main users of ropes for permanent mooring systems, the oil and gas industry has opted for these components because they possess performance characteristics and economies of scale which are in many respects superior to steel components. Given this accrued experience, it is unsurprising that several marine renewable energy (MRE) device developers have utilised synthetic ropes, motivated by the need to specify economical, reliable and durable mooring systems. Whilst these components are potentially an enabling technology for the MRE sector, this is a new field of application which can feature highly dynamic mooring tensions and consequently existing certification practices may not be directly applicable. Based on the expertise of the authors, this paper provides a state-of-the-art overview of synthetic ropes in the context of MRE mooring systems, including key information about aspects of specification (performance attributes, classification and testing) as well as application (installation, degradation, maintenance, inspection and decommissioning). It is the intention of this review to provide valuable insight for device developers who are considering using ropes in the specification of fit for purpose mooring systems.

358. WELLER, S.D., THIES, P.R., GORDELIER, T., DAVIES, P. & JOHANNING, L.: "The Role of Accelerated Testing in Reliability Prediction", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
The transition from the early stages of marine renewable energy (MRE) device development towards pre-commercial status involves rigorous design validation before full-scale testing. The main aim of Technology Readiness Levels 4-6 is to prove that the concept can deliver the required power production performance and also that a level of system reliability is achieved to ensure sufficient availability. Both of these metrics are crucial to obtaining competitive levelised cost of energy. The current state of the MRE sector means that reliability data is sparse or commercially sensitive. Device developers are therefore forced to base reliability predictions on physical testing, detailed numerical analysis or in the absence of these, generic (and potentially unsuitable) failure rate databases. Generic data will only provide a crude estimate of component or subsystem reliability unless modified to suit the application. More accurate estimates of component and subsystem reliability are possible through accelerated testing. As part of the DTOcean (Optimal Design Tools for Ocean Energy Arrays) project, results from physical tests involving synthetic ropes and shackles are used to demonstrate how quantitative accelerated testing can be used to bridge the gap between generic failure rates and those which are applicable to MRE mooring applications.

359. WELLER, S.D., THIES, P.R., GORDELIER, T., HARNOIS, V., PARISH, D.N. & JOHANNING, L.: "Navigating the Valley of Death: Reducing Reliability Uncertainties for Marine Renewable Energy", *Proc. of the International Conference on Offshore Renewable Energy, Glasgow, United Kingdom*, 15-17 Sep 2014
Technology Readiness Levels (TRLs) are a widely used metric of technology maturity and risk for marine renewable energy (MRE) devices. To-date, a large number of device concepts have been proposed which have reached the early validation stages of development (TRLs 1-3). Only a handful of mature designs have attained pre-commercial development status following prototype sea trials (TRLs 7-8). In order to navigate through the aptly named valley

of death (TRLs 4-6) towards commercial realisation it is necessary for new technologies to be de-risked in terms of component durability and reliability. Due to a lack of deployment experience a conservative design approach is often adopted utilising existing offshore certification guidance. Developers must therefore balance the competing requirements of designing economically viable and yet robust devices. Reliability assessment (including physical component testing and statistical analysis) enables device developers to determine component suitability and reliability in a cost-effective way prior to full-scale prototype deployment.

360. YOUNG, A.: "Capabilities and limitations of ADCPs for turbulence measurements", *In Proceedings of the IEEE OCEANS 2014, St Johns, Newfoundland, Canada*, DOI: 10.1109/OCEANS.2014.7003057, Sep-14
The lifespan of a tidal turbine is strongly affected by the unsteady loading it experiences, so knowledge of the mean flow speed is not sufficient: unsteadiness must also be quantified. One of the most common turbulence measurement devices in the marine environment is the Acoustic Doppler Current Profiler (ADCP). The variance of steady velocity measurements from ADCPs has been studied in detail, but very little attention has been given to the fundamental limits of ADCPs in terms of the frequencies and lengthscales that they can capture. In this paper, it is shown that the ADCP acts as a low-pass filter to eddies and that even optimistic calculations predict significant attenuation at lengthscales up to ten times the blade chord of a typical tidal turbine. For a typical 40 m deep channel wavelengths below 3-4 m are attenuated by 90% or more. Those eddies that are not filtered out are then subject to a distortion that will either amplify or attenuate the signal depending on the precise turbulencecharacteristics of the site in question. While this low-pass filtering may alter some global statistics by truncating the observed spectrum, it is most damaging when data is extracted for particular frequencies, as a turbine designer may do when assessing unsteady loading and fatigue life. It is therefore recommended that high-resolution turbulence data, e.g. from a hotwire, is captured over part of the water column and that this is used to calibrate ADCP data.

Novel Marine Energy Systems and Components

362. ASHTON, I.G.C. & JOHANNING, L.: "On errors in low frequency wave measurements from wave buoys", *Ocean Engineering*, *vol. 95*, pp. 11–22, DOI: 10.1016/j.oceaneng.2014.11.033, 01-Feb-15
Floating wave buoys are widely considered as a global standard for wave data. Marine renewable energy presents a relatively new industry for wave measurements, requiring a high level of accuracy for applications including resource assessment, performance assessment and engineering design. This study draws on the unique deployment of four identical wave buoys in close proximity and a period of data from a free-floating buoy to classify spurious low frequency measurements as erroneous. The nature of the occurrence of these errors, and their effect on the validity of measurements are also examined. The work shows that the errors are directly related to the drag forces on the buoy, but with a correctly designed filter, the effect of the errors on the wave measurements can be mitigated. A variable filter process is described which improves the accuracy of measurements captured by these buoys. This is recommended for all interpretation of these data, and is essential for any detailed statistical analysis.

363. 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, Part M: Journal of Engineering for the Maritime Environment*, DOI: 10.1177/1475090211425143, 2012
This paper describes a non-linear power take-off system within a buoyant heaving wave energy converter. The power take-off uses the relative velocity between the main structure of the wave energy converter and an inertial referenced mass contained within its outer envelope. The power take-off consists of a linear spring and a quadratic damper. In this paper the mathematical principles behind a working time domain simulation of a non-linear power take-off 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 power take-off 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 wave energy converter.

364. BARAJAS-SOLANO, I., MUELLER, M. & KIPRAKIS, A.: "Active Magnetic Bearings for Linear Generators", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
This document presents a brief introduction to wave energy converters(WEC), focusing on linear generators and its design issues proposing novel solutions. The development of new concepts in the application of magnetic bearings for linear generators is discussed. In particular passive and active magnetic bearing concepts for tubular and planar machines are presented. Electromagnets are combined with permanent magnet and Halbach arrays, and a simple design study shows the benefits of using a hybrid electromagnet-Halbach array.

365. BARAJAS-SOLANO, I.J. & MUELLER, M.A.: "Active Magnetic Bearings Using Air-Cored Coils Halbach Array in a Linear Wave Energy Converter", *2nd Asian Wave and Tidal Energy Conference, Japan*, 28 July - 1 Aug 2014
This paper aims to demonstrate a proposed new array topology of air-cored electromagnets. This device is designed to generate repulsion forces between a Litz wire track and the Halbach array thus providing a magnetic bearing in a linear generator. The benefits and advantages of this design will be explained and explored within this paper.

366. 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
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 1.2MW tidal current energy converter associated with a 1-MWh storage system of modest efficiency can offer significant advantages over the generator working alone.

367. BUCKLAND, H.C., MASTERS, I., ORME, J.A.C. & BAKER, T.: "Cavitation Inception and Simulation in BEMT for Modelling Tidal Stream Turbines", *Institution of Mechanical Engineers, Part A: Journal of Power and Energy,*, *vol. 227*, *issue. 4*, pp. 479-485, DOI: 10.1177/0957650913477093, 2013
Blade element momentum theory (BEMT) is an analytical modelling tool that describes the performance of turbines by cross-referencing one-dimensional momentum theory with blade element theory. Each blade is discretised along its length and the dynamic properties of torque and axial force are determined. A compatible

cavitation detection model is introduced to indicate any cavitating blade elements. Cavitation occurrence is dependent on proximity to the free surface, the incident flow velocity and inflow angle and the blade cross-section aerofoil shape. The shock waves associated with cavitation can significantly damage the blade surface and reduce performance; therefore, this model is a useful addition to BEMT and can be used in turbine design to minimise cavitation occurrence. The results are validated using the cavitation experiment observations.

368. CHAPLIN, J.R., FARLEY, F.J.M., GREAVES, D.M., HANN, M., KURNIAWAN, A. & COX, M.: "Numerical and experimental investigation of wave energy devices with inflated bags", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Our study is concerned with a class of wave energy devices with air-filled compressible volumes. As the volume expands and contracts under wave action, air is pumped intoa separate volume via a self-rectifying turbine. Here we considerdevices where the compressible volume is in the form of aninflated bag, which may be surface-piercing or completely sub-merged. The bag is essentially a lobed balloon inflated to a certainpressure, where loads are carried in the meridional direction bya number of uniformly spaced tendons. The paper looks mainlyinto the behaviour of a device with a surface-piercing bag instill water, where it is found by numerical calculations as well asphysical model tests that depending on the amount of air insidethe bag, two different equilibrium bag shapes are possible for thesame internal pressure, thus offering a way of tuning the deviceto a range of wave periods. Physical model tests and preliminarynumerical modelling of the device in the dynamic case are alsodescribed, where, firstly, the device is forced to oscillate in waterby pumping air into and out of the bag and, secondly, the deviceis taking off power under incident wave excitations.

369. CROZIER, R., BAILEY, H., MUELLER, M., SPOONER, E., & MCKEEVER, P.: "Analysis, design and testing of a novel direct-drive wave energy converter system", *IET Renewable Power Generation*, *vol. 7*, *issue. 5*, pp. 565-573, 2013
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.

370. EDMUNDS, M., WILLIAMS, A.J., MASTERS, I. & CROFT, T.N.: “An enhanced disk averaged CFD model for the simulation of horizontal axis tidal turbines” *Renewable Energy, vol. 101,* pp. 67-81, doi:10.1016/j.renene.2016.08.007, ISSN 0960-1481, Feb 2017
Simulating fully resolved Horizontal Axis Tidal Turbine (HATT) geometry for a time period great enough to resolve a fully developed wake, and accurately predict power and thrust characteristics, is computationally very expensive. The BEM-CFD method is an enhanced actuator disk and is able to reduce the computational cost by simulating a time averaged downstream velocity field. Current implementations fall short of accurately determining tip losses, which are a function of the hydrofoil geometry. This work proposes a method of addressing this shortfall by modifying the angle of attack to conform to the constraints outlined in Prandtl's lifting line theory, i.e. the zero lift angle of attack at the hydrofoil tip. The revised model is compared to existing BEM-CFD methods and validated against experimental data. The revised BEM-CFD method presented in this work shows a significant improvement over previous BEM-CFD methods when predicting power and thrust. The coefficient of power is reduced from 0.57 (approx. 30% above experiment) to 0.44 (approx. 3% above experiment). An increase in turbulence intensity in the rotor region, in particular at the wake boundary, improves the recovery of the wake without the addition of empirical turbulence source terms. Good correlation with experimental results for power, thrust and wake prediction, is observed. The model may also be applied to wind turbines.

371. FOLLEY, M. & WHITTAKER, T.: "Identifying promising wave energy converter technologies", *13th World Renewable Energy Conference, London, UK.*, 3-8 Aug 2014
The exploitation of wave energy is in the early stages of development. Like the development of wind energy during the first half of the twentieth century, there is currently no standard system for the commercial extraction of wave energy. This creates both an opportunity and challenge for developers and investors. An opportunity, because it is likely that significant IP remains to be developed, with its associated rewards, and a challenge, because it is not yet clear which fundamental method(s) of exploitation will become dominant in the future. Currently, it is possible to identify at least five fundamentally different types of wave energy converters, and within each one of these categories there are typically many variations resulting in over a 100 different wave energy converter technologies being developed. Undoubtedly, the developers of each technology believe that they have a winning concept and in addition have some evidence to support this view; unfortunately, it is likely that the vast majority of these developers will be disappointed. For wave energy to reach commercial viability, it will be necessary to accurately identify promising wave energy technologies. This chapter investigates the reasons why such a large range of technologies is currently being supported and developed. This investigation centres on identifying the particular

assumptions, views and perceptions that may be held by technology stakeholders and how these factors may influence wave energy converter design to both the benefit and detriment of the technology and industry. In addition, it includes further analysis of how these factors may be related to both the hydrodynamics and economics of wave energy converters. The chapter concludes with a graphical organisation of wave energy converter technologies that illustrates their fundamental development characteristics and supports the identification of promising technologies.

372. GAURIER,B., GERMAIN, G., FACQ, J.V., JOHNSTONE, C.M., GRANT, A.D., DAY, A.H., NIXON, E., DIFELICE, F. & COSTANZO, M.: "Tidal Energy 'Round Robin' Test Comparisons between Towing Tanks and Circulating Tanks.", *International Journal of Marine Energy*, DOI: 10.1016/j.ijome.2015.05.005, Dec-15
One key step of the industrial development of a tidal energy device is the testing of scale prototype devices within a controlled laboratory environment. At present, there is no available experimental protocol which addresses in a quantitative manner the differences which can be expected between results obtained from the different types of facilities currently employed for this type of testing. As a consequence, where differences between results are found it has been difficult to confirm the extent to which these differences relate to the device performance or to the test facility type. In the present study, a comparative "Round Robin" testing programme has been conducted as part of the EC FP VII MaRINET program in order to evaluate the impact of different experimental facilities on the test results. The aim of the trials was to test the same model tidal turbine in four different test facilities to explore the sensitivity of the results to the choice of facility. The facilities comprised two towing tanks, of very different size, and two circulating water channels. Performance assessments in terms of torque, drag and inflow speed showed very similar results in all facilities. However, expected differences between the different tank types (circulating and towing) were observed in the fluctuations of torque and drag measurements. The main facility parameters which can influence the behaviour of the turbine were identified; in particular the effect of blockage was shown to be significant in cases yielding for high thrust coefficients, even at relatively small blockage ratios.

373. GEBRESLASSIE, M.G., TABOR, G.R. & BELMONT, M.R.: "Numerical simulation of a new type of cross flow tidal turbine using OpenFOAM - Part I: Calibration of energy extraction", *Renewable Energy*, *vol. 50*, pp. 994-1004, DOI: 10.1016/j.renene.2012.08.065, 2013
This paper introduces a new CFD based Immersed Body Force (IBF) model, and examines the performance of a new type of tidal turbine, the Momentum Reversal Lift (MRL) turbine, developed by Aquascientific Ltd using the open source computational fluid dynamics (CFD) code OpenFOAM. The IBF model was added as a forcing function into the existing large eddy simulation model to create a momentum change in the fluid flow induced by the MRL turbine. An experimental study was performed on a small scale model to determine the operating efficiency of the turbine and the data was used to validate the IBF model. The power output curves from both the IBF model and the experiments showed good agreement in most of the data except for a few discrepancies at higher torques, due to venturi flow created by the proximity of the computational domain's wall boundary to the turbine. Thus the results presented in this paper show the fidelity of the IBF model and can be used for different tidal turbine numerical modelling.

374. GORDELIER, T., PARISH, D., THIES, P.R. & JOHANNING, L.: "A novel mooring tether for highly dynamic offshore applications; mitigating peak and fatigue loads via selectable axial stiffness", *Journal of Marine Science and Engineering (JMSE), Special Issue "ASRANet - Offshore Renewable Energy"*, *vol. 3:1287-1310*, DOI: 10.3390/jmse3041287, 22-Oct-15
Highly dynamic floating bodies such as wave energy convertors (WECs) require mooring lines with particular mechanical properties; the mooring system must achieve adequate station keeping whilst controlling mooring tensions within acceptable limits. Currently, fibre ropes are commonly used but many mooring designers are seeking alternative solutions that can offer more favourable mechanical properties. The compliance offered by a mooring system will depend largely on the axial stiffness of the mooring lines. Whilst fibre ropes can offer lower axial stiffness than alternatives such as chain and wire rope, there remains a fundamental conflict which prohibits the free selection of axial stiffness properties. This conflict exists because the axial stiffness is strongly governed by the minimum breaking load (MBL) of the rope. The specified MBL must be sufficient to accommodate the predicted peak tension loads with an appropriate factor of safety (FOS) to cater for uncertainties and degradations. In achieving a sufficient MBL, the designer is often forced to accept a higher axial stiffness than is preferred. A potential benefit of reducing the axial stiffness of a mooring line is the reduction of peak loads and fatigue loads. This allows a reduction in mass of both the floating body and the mooring system, thus reducing costs and improving system reliability. This work describes the 'Exeter Tether', an innovation in mooring tether design which decouples the axial stiffness properties from the MBL of the tether. Removing this constraint allows a tether to be specified according to both MBL and axial stiffness. The principals behind the novel tether design are introduced along with an outline of 10 prototype tether variants manufactured in collaboration with Lankhorst Ropes. Results from the proof of concept tests at the University of Exeter's Dynamic Marine Component Test

Facility (DMaC) are presented together with preliminary findings from sea trials at the South West Moorings Test Facility (SWMTF). The anticipated load mitigation introduced via the mooring tether is investigated and the implications for system design are discussed.

375. GRACIE, K., JOHNSTONE, C.M., MURRAY, R.E., DOMAN, D.A. & PEGG, M.J.: "Fixed-Pitch Blades for Passive-Feather Power Regulation of Second-Tier Site Tidal Turbines", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
The tidal energy industry requires the adoption of mechanically simple designs which optimise power capture over the tidal cycle. The first stages of a project investigating the use a passive-feather method to regulate the power output of a tidal turbine through PWM load control are presented. Theoretical and experimental investigations were undertaken to analyse the engineering system requirements and restraints associated with the use of this method. It is shown that, due to the increased terminal voltage loads as the rotor speeds up, the use of this method will require the increase in λ to be limited. Furthermore, it is shown that a new blade design is likely to be required for this method. In designing this curve, a balance is required to be struck between producing a realistic curve that may be approximated in real life, and limiting the increase in λ. Consideration of the increase in voltage with λ will play a large role in the future of this research.

376. GRACIE, K., JOHNSTONE, C.M., NAVALAINEN, T.M., MURRAY, R.E., DOMAN, D.A. & PEGG, M.J.: "Development of a blade design methodology for overspeed power-regulated tidal turbines.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
The range and variability of flow velocities in which horizontal axis tidal stream turbines operate introduces the requirement for a power regulation method in the system. Passive overspeed power regulation (OSPR) has the potential to improve the structural robustness and decrease the complexity associated with active pitch power regulation methods, while removing the costs associated with the generator over-capacity required for passive-stall power regulation. This paper presents the development of a methodology for the design of blades to be used in such systems. The pitch setting, twist and chord distribution were set as variable input parameters. Rotor performance has been broken down into OSPR performance metrics. Three visualnumerical tools have been developed: OSPR performance metrics were used in conjunction with a sensitivity analysis approach to develop a design space; full cavitation inception analyses gave plots of converging cavitation and pressure terms for each blade section; the local angle of attack and torque distribution across the blade designs were plotted at key turbine operation states. The prevention of cavitation has been highlighted as a major driver for speed-limiting design alterations. Alterations to pitch setting and twist distribution are shown to have most impact upon this design requirement; coupled with such alterations, changes made to chord distribution have been shown to increase the maximum efficiency.

377. GÖTEMAN, M., ENGSTRÖM, J., ERIKSSON, M., LEIJON M., HANN, M., RANSLEY, E. & GREAVES, D.: "Wave Loads on a Point-Absorbing Wave Energy Device in Extreme Waves", *Journal of Ocean and Wind Energy*, *vol. 2*, *issue. 3*, pp. 176-181, DOI: 10.17736/jowe.2015.mkr03, *ISSN: 2310-3604*, 2015
The survivability of a 1:20 scale point-absorbing Wave Energy Converter (WEC) model is considered in extreme wave tests with focused waves embedded in regular wave backgrounds and with time series of irregular waves. The wave heights were many times higher than the maximal stroke length of the device. Three different float geometries were used in the tests. The peak loads were measured and compared for extreme waves embedded in background waves with a range of periods and phase relations and with different values of Power Take-Off (PTO) damping.

378. HANN, M., GREAVES, D. & RABY, A.: "Snatch loading of a single taut moored floating wave energy converter due to focussed wave groups", *Ocean Engineering*, *vol. 96*, pp. 258-271, DOI: 10.1016/j.oceaneng.2014.11.011, 01-Mar-15
This paper concerns experimental measurements of the interaction of a taut moored floating body, representing a wave energy converter in survivability mode, with extreme waves. Focussed wave groups, based initially on NewWave theory, are used to generate the extreme waves, with crest amplitude exceeding the mooring's design capacity. Two data sets are presented and discussed. In the first the influence of wave steepness on model response and mooring load is investigated using non-breaking focussed wave groups. In the second the influence of wave breaking location is investigated using a plunging breaking wave. Both data sets exhibit snatch loading as the extension of the mooring is exceeded. The magnitude of this loading is not found to be strongly dependent on wave steepness, while the following motion response of the body is. Breaking location has a much greater effect than wave steepness on the magnitude of the mooring load, while significant influence of the body motion and displacement on the mooring load is demonstrated. Evidence is provided that the use of individual focussed wave groups is inadequate to assess fully the extreme loads experienced by a taut moored WEC due to the demonstrated dependence of mooring load on the body's motion and displacement.

379. HARDING, S.F. & BRYDEN, I.G.: "Generating controllable velocity fluctuations using twin oscillating hydrofoils", *Journal of Fluid Mechanics*, *vol. 713*, pp. 150-158, Oct-12
An experiment apparatus has been previously developed with the ability to independently control the instantaneous flow velocity in a water flume. This configuration, which uses two pitching hydrofoils to generate the flow fluctuations, allows the unsteady response of submerged structures to be studied over a wide range of driving frequencies and conditions. Linear unsteady lift theory has been used to calculate the instantaneous circulation about two pitching hydrofoils in uniform flow. A vortex model is then used to describe the circulation in the wakes that determine the velocity perturbations at the centreline between the foils. This paper introduces how the vortex model can be discretized to allow the inverse problem to be solved, such that the foil motions required to recreate a desired velocity time series can be determined. The results of this model are presented for the simplified cases of oscillatory velocity fluctuations in the vertical and stream-wise directions separately, and also simultaneously. The more general case of two-dimensional aperiodic velocity fluctuations is also presented, which demonstrates the capability of configuration between the suggested frequency limits of $0.06 \leq k \leq 1.9$.

380. HOLMES, B., PRADO, M., MCCOMBES, T. JOHNSTONE C., KOFOED, J.-P., NEUMANN, F., RETZLER, C. & BITTENCOURT-FERREIRA, C.: "EquiMar: Sea Trial Manual", pp. 1-109, *ISSN: 978-0-9508920-4-7*, 2011
The three EquiMar engineering protocols were designed in conjunction with the International Energy Agency's Implementing Agreement on Ocean Energy Systems (IA-OES) 5 Stage development programme for wave energy converters (WECS). The objective is to complement that overview document by detailing the project planning and technical requirements necessary to safely and successfully advance the design of a WEC with minimum risk and uncertainty. This manual addresses Stages 3 and 4 and introduces guidelines for the testing, monitoring and evaluating of the sea trial of solo devices. The US Department of Energy's (DOE) Technology Readiness Assessment scheme for the development of marine hydrokinetic (MHK) devices also follows a similar format but with 9 Technology Readiness Levels (TRL)

381. JEFFREY, H., SEDGWICK, J. & GERRARD, G.: "Public funding for ocean energy: a comparison of the UK and US", *Technological Forecasting and Social Change*, *vol. 84*, pp. 155-170, DOI: 10.1016/j.techfore.2013.08.006, 2013
This paper presents a detailed analysis of the activities in which ocean energy public funding in the UK and the U.S. has been spent. It conducts a direct comparison of funding from the U.S. Department of Energy (DoE) with that from the UK and Scottish Governments. UK investment in the sector has been relatively sustained and has increased since 2002. Almost $295 million has been spent in total, across multiple funding bodies. U.S. spending began with the establishment of the Marine Hydrokinetic division of the DoE Water Power Programme in 2008, which has administered all non-defence federal public funding for the sector. U.S. funding has steadily increased since 2008, with the total funding approaching $92 million. Approximately 40% of total U.S. spending has been on underpinning R&D activities, compared to 20% in the UK which has had a larger focus on funding full scale test infrastructure and related deployment activities. Whilst the U.S. has seen steadily increasing funding for all activities to support the sector, UK funding for deployment activities, especially test centre infrastructure and demonstration activities, has not been sustained and has had significant peaks and troughs in recent years as funding programmes and initiatives have started and finished.

382. JOHNSTONE, C.M. & JO, C.H.: "The engineering challenges in delivering robust, cost effective technology for an international tidal energy industry", *Proceedings of Asian Wave and Tidal Energy Conference, Tokyo, Japan*, Aug-14
Tidal energy technologies currently being deployed are expensive and considered not the be economically viable. The technologies are heavy resulting in high capital cost of plant and installation costs. They contain complex engineering and control systems therefore incurring high operational and maintenance costs. For tidal energy to be commercially acceptable, significant engineering challenges need addressing to reduce weight, complexity to reduce capital and operational costs and reduce installation costs. This paper identifies these challenges and activities being undertaken to address these.

383. KURNIAWAN, A., GREAVES, D. & CHAPLIN, J.: "Wave energy devices with compressible volumes", *Proceedings of the Royal Society A*, *vol. 470*, *issue. 2172*, DOI: 10.1098/rspa.2014.0559, 22-Oct-14
We present an analysis of wave energy devices with air-filled compressible submerged volumes, where variability of volume is achieved by means of a horizontal surface free to move up and down relative to the body. An analysis of bodies without power take-off (PTO) systems is first presented to demonstrate the positive effects a compressible volume could have on the body response. Subsequently, two compressible device variations are analysed. In the first variation, the compressible volume is connected to a fixed volume via an air turbine for PTO. In the second variation, a water column separates the compressible volume from another volume, which is fitted with an air turbine open to the atmosphere. Both floating and bottom-fixed, axisymmetric, configurations are considered, and linear analysis is employed throughout. Advantages and disadvantages of each device are examined in detail. Some configurations with displaced volumes less than 2000m3 and with constant turbine

coefficients are shown to be capable of achieving 80% of the theoretical maximum absorbed power over a wave period range of about 4s.

384. KURNIAWAN, A. & GREAVES, D.: "Broad-banded wave power absorption with submerged balloons", *IET Renewable Power Generation Journal*, DOI: 10.1049/iet-rpg.2016.0044, 2016
It is well-known that to optimally absorb energy from ocean waves, a wave energy device needs to oscillate with optimum amplitude and phase. A wave energy device in a real sea needs to operate as close as possible to this optimum condition for a range of wave periods, wherein lies the challenge. This challenge is particularly pertinent for point absorbers, which, by definition, are much smaller than the incident wavelengths. When oscillating in the conventional rigid-body heave, they are inherently narrow-banded. In this paper, we show that point absorbers in the form of submerged air-filled balloons could have a surprisingly broad wave absorption bandwidth. These devices oscillate not in the conventional rigid-body heave, but in a pulsating mode, whose natural period of oscillations is determined not by the submerged volume of the oscillating body, but by the volume of air provided in the system, which acts as an air spring.

385. KURNIAWAN, A., GREAVES, D., HANN, M. & CHAPLIN, J.: "Multi-resonant compressible wave energy devices", *29th International Workshop on Water Waves and Floating Bodies, Osaka, Japan*, 30 March - 2 April 2014
We propose two multi-resonant wave energy devices with compressible volumes. One is fixed to the seabed. The other is floating. Linear mathematical models, assuming no losses, predict that devices with displaced volumes of about 3000 m3 are capable of absorbing 80% of the theoretical limit for a wave period range of 5 seconds.

386. LANDE-SUDALL, D., STALLARD, T. & STANSBY, P.K.: "Energy yield and loads for co-located offshore wind and tidal stream turbines", *RENEW*, Oct-16
Deployment of co-located wind and tidal stream turbines is proposed as a method for reducing cost of electricity generation from either technology individually. Energy yield for wind turbines is modelled using an eddy viscosity wake model and for tidal turbines using a method of self-similar superposition of wake deficits. Yaw strategy is considered for the tidal turbines, finding that although a continuous yaw strategy generates highest yield, a slack-tide strategy offers a suitable compromise with mechanical complexity. A case-study of the MeyGen site in the Pentland Firth is considered for co-location. The addition of 12MW of wind capacity to a 20MW tidal array results in a twofold increase in annual energy yield, compared to operating the tidal turbines alone. Phasing of the tidal cycle means that during a neap tide, the combined system may be entirely dependent on wind generation, but during a spring tide there is a regular tidal supply. Steady state loads for wind and current are also modelled for a braced monopile support structure. For tidal turbines only, the mean probable loads vary by 12% across the array. Net horizontal force on the tidal turbines is 28% greater than on the wind turbines. However, due to the distance between turbine axis and base, the magnitude of the base moment for the combined support structure is found to be driven by wind loading.

387. LAWRENCE, J., SEDGWICK, J., JEFFREY, H. & BRYDEN, I.: "An Overview of the UK Marine Energy Sector", *Proceedings of the IEEE*, *vol. 10*, *issue. 4*, pp. 876-890, DOI: 10.1109/JPROC.2012.2235055, 2013
This paper gives a historical overview of the development of the U.K. marine energy sector from its academic beginnings in the early 1970s. It includes discussion on government support policies and where the sector might develop up to and beyond the end of this decade. The paper also presents two very different projects: the European Marine Energy Centre in Orkney, U.K., and the forthcoming All Waters Current and Wave Test Facility in Edinburgh, U.K., as examples of capital investment in the sector.

388. LE, H., COLLINS, K.M., GREAVES, D. & BELLAMY, N.: "Mechanics and Materials in Design of Biomimetic Diaphragm for Wave Energy Converter", *Materials and Design*, *vol. 79*, pp. 86–93, DOI: 10.1016/j.matdes.2015.04.041, 2015
The design of a flexible wave energy device with a spine shape diaphragm proposed by Sea Energy Associates Ltd. was analysed. The operation of the device involves reversible buckling of a diaphragm in both longitudinal and transverse directions. The design constraints of the diaphragm were identified and Cambridge Engineering Selection software was applied to select candidate materials for the diaphragm structure. Best candidates of materials were identified for both laboratory scale and industrial scale. The initial curvature of the diaphragm was analysed using the minimum energy principle. The theoretical predictions of transverse deflection and longitudinal radius of curvature were in good agreement with measurements taken on a 1/10th scale-model of the diaphragm structure.

389. LEYBOURNE, M., BATTEN, W.M.J., BAHAJ, A.S., MINNS, N. & O'NIANS, J.: "Preliminary design of the OWEL wave energy converter pre-commercial demonstrator", *Renewable Energy*, *vol. 61*, pp. 51-56, DOI: 10.1016/j.renene.2012.08.019, 2014
The consortium responsible for the next stage of development of the OWEL wave energy converter will construct and test a large scale, pre-commercial demonstrator. It is expected that this will be installed at Wave Hub during

2013 and grid connected for a testing period lasting around 12 months. This paper reports on the preliminary design work being undertaken in the development of the marine demonstration device. This concentrates primarily on producing a fully costed design by detailing the hydraulic design and aspects of stability as well as providing insight into various design features such as the power take-off, naval architecture, moorings and control. The design is being largely informed by the results of a 15 month research project funded by the South West Regional Development Agency (SWRDA) in which the performance was determined and a detailed techno-economic model for a large scale OWEL device was generated.

390. LI, G. & BELMONT, M.R.: "Model Predictive Control of a Sea Wave Energy Converter: A Convex Approach", *19th IFAC World Congress, Cape Town, South Africa*, 2014
This paper investigates model predictive control (MPC) of a sea wave energy converter(WEC). A novel objective function is adopted in the MPC design, which brings obvious benefits: First, the quadratic program (QP) derived from this objective function can be easily convexified, which facilitates the employment of existing efficient optimization algorithms. Second, this novel design can trade off the energy extraction, the energy consumed by the actuator and safe operation. The effectiveness of this MPC strategy is demonstrated by numerical simulations.

391. LI, G. & BELMONT, M.R.: "Model Predictive Control of an array of Wave Energy Converters", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
This paper investigates model predictive control (MPC) of sea wave energy converters (WECs). We start withthe case of a single WEC. A novel objective function is adoptedin the MPC design, which brings obvious benefits: First, thequadratic program (QP) derived from this objective function canbe designed to be convex, which facilitates the employment ofthe existing efficient optimization algorithms. Second, this noveldesign can trade off the energy output extraction, the energyconsumed by the power electronic system and the constraintsatisfaction for safe operation. All these benefits promote thereal-time application of MPC on a WEC and reduced cost ofhardware. Furthermore, a decentralized MPC control strategyis developed for the control of a modest-sized and highly-coupled array of WECs. Each WEC is controlled by its ownMPC controller, and these MPC controllers coordinate with eachother by taking into account the internal waves generated byother WECs and sharing the control inputs and states of theadjacent WECs. Therefore this decentralized MPC can not onlyapproximate the optimal control for the whole array but alsodistribute the computational burden to local MPC controllers,which improves its practical implementation. Simulation resultsdemonstrate the efficacy of the proposed control strategies.

392. LI, G., & M. BELMONT, M.: "Model predictive control of sea wave energy converters Part I: a convex approach for a single device", *Renewable Energy*, *vol. 69*, pp. 453-463, DOI: 10.1016/j.renene.2014.03.070, 2014
This paper investigates model predictive control (MPC) of a single sea wave energy converter (WEC). By using control schemes which constrain certain quantities, such as the maximum size of the feedback force, the energy storage for actuators and relative heave motion, it is possible for control to not only improve performance but to directly impact strongly on design and cost. Motivated by this fact, a novel objective function is adopted in the MPC design, which brings obvious benefits: First, the quadratic program (QP) derived from this objective function can be easily convexified, which facilitates the employment of existing efficient optimization algorithms. Second, this novel design can trade off the energy extraction, the energy consumed by the actuator and safe operation. Moreover, an alternative QP is also formulated with the input slew rate as optimization variable, so that the slew rate limit of an actuator can be explicitly incorporated into optimization. All these benefits promote the real-time application of MPC on a WEC and reduced cost of hardware.

393. LI, G., WEISS, G., MUELLER, M., TOWNLEY, S. & BELMONT, M.: "Wave energy converter control by wave prediction and dynamic programming", *Renewable Energy*, *vol. 48*, pp. 392-403, DOI: 10.1016/j.renene.2012.05.003, Dec-12
We demonstrate that deterministic sea wave prediction (DSWP) combined with constrained optimal control can dramatically improve the efficiency of sea wave energy converters (WECs), while maintaining their safe operation. We focus on a point absorber WEC employing a hydraulic/electric power take-off system. Maximizing energy take-off while minimizing the risk of damage is formulated as an optimal control problem with a disturbance input (the sea elevation) and with both state and input constraints. This optimal control problem is non-convex, which prevents us from using quadratic programming algorithms for the optimal solution. We demonstrate that the optimum can be achieved by bang–bang control. This paves the way to adopt a dynamic programming (DP) algorithm to resolve the on-line optimization problem efficiently. Simulation results show that this approach is very effective, yielding at least a two-fold increase in energy output as compared with control schemes which do not exploit DSWP. This level of improvement is possible even using relatively low precision DSWP over short time horizons. A key finding is that only about 1 second of prediction horizon is required, however, the technical difficulties involved in obtaining good estimates necessitate a DSWP system capable of prediction over tens of seconds.

394. LOK, K.S., STALLARD T.J., STANSBY P.K. & JENKINS N.: "Optimisation of a Clutch-Rectified Power Take Off System for a Heaving Wave Energy Device in Irregular Waves with Experimental Comparison", *Journal of Marine Energy*, *vol. 8*, pp. 1-16, DOI: 10.1016/j.ijome.2014.09.001, Dec-14
Many devices have been proposed for generating electricity from the oscillatory motion of a floating body in waves which are generally irregular. This study undertakes numerical modelling and small-scale experimental testing of a power take-off system for a heaving float. A power take off system is employed to provide high speed rotational input to a standard induction generator. A numerical model of the coupled hydrodynamic and electrical system is described with particular focus on the effect of generator control strategy on the time-varying response and power output of the system. The numerical model with three empirical hydrodynamic coefficients is calibrated against experimental measurements in regular waves. The control method includes a static characteristic and a proportional integral (PI) controller to maximise average power output whilst reducing the peak rate of change of torque in the driveshaft compared to a system with no control applied. The control strategy is implemented within a model drive-train with a geometric scale of 1:67. Experimental tests are reported and model predictions of time-varying response have a form similar to the measured response. Average power output from irregular waves is predicted within 11% for frequencies less than 1.3 Hz (periods greater than 6.3 s full scale) and wave heights greater than 30 mm (2 m full scale).

395. LUXMOORE, J., GREY, S., NEWSAM, D., THIES, P.R. & JOHANNING, L.: "Performance Assessment of a Novel Active Mooring System for Load Reduction in Marine Energy Converters", *International Conference on Ocean Energy (ICOE). Edinburgh, UK.*, 2016

396. Mooring systems affect extreme and fatigue loading in moored wave and tidal stream energy converters driving reliability, device survival and energy extraction efficiency. A novel mooring system referred to as the Intelligent Active Mooring System (IAMS) combines a load-extension curve which can be actively varied in response to the prevailing met-ocean conditions with a high minimum breaking load. Prototype test results demonstrate the working principle and validate the performance characteristics. The tests have established the component behaviour for different design settings and load profiles show that the system allows a wide range of response characteristics and reliable operation under single system failure mode. Numerical model studies comparing IAMS performance against existing solutions show potential for significant overall system cost reduction.

397. MCCOMBES, T., JOHNSTONE, C. & GRANT, A.: "Navier-Stokes modelling for contra-rotating tidal turbines", *EWTEC 2011, Southampton, UK*, Sep-11
This paper describes the comparison of analysis methods for coaxial contra-rotating turbines using two blade element methods and a Navier-Stokes method based on the vorticity transport equations. The blade element methods are the readily soluble pair in which the downstream rotor is either considered to operate either in the same plane as the upstream rotor, or in the fully developed wake of the upstream rotor. The in-house vorticity transport code V3D is used as it has been specifically designed with unsteady, wake dynamics driven problems in mind. This solves for the time varying wake of multiple moving bodies and is capable of preserving the vortex wake for the durations required to adequately resolve coaxial turbine problems. Results for single– and multi–rotor configurations are presented, compared and discussed.

398. MCNATT, J.C., VENUGOPAL, V. & FOREHAND, D.: "A novel method for deriving the diffraction transfer matrix and its application to multi-body interactions in water waves", *Ocean Engineering*, *vol. 94*, pp. 173-184, DOI: 10.1016/j.oceaneng.2014.11.029, Jan-15
A matrix method was developed by Kagemoto and Yue (1986) to compute interactions between multiple three-dimensional bodies subjected to linear water waves. The approach leads to a significant reduction in computational time versus the direct method, in which the boundary value problem is solved for all bodies simultaneously. An essential component of the theory is the so-called diffraction transfer matrix, a linear operator defined for each unique geometry. However, the diffraction transfer matrix is not a standard product of a linear wave computation, for one, because it is based around an unusual representation of incident waves, that is, as partial cylindrical waves. In this paper, a new method is presented to compute the diffraction transfer matrix from plane incident waves, which enables one to derive it from standard wave-body software or experiments. Additionally, a new linear operator – the force transfer matrix, is presented, which can also be determined by usual means. Herein, the interaction theory calculation is verified against direct method results from the linear wave-body software, WAMIT, and then applied to compute absorbed power and wave field effects on a medium-sized array in spectral seas and on a large farm of 101 wave energy converters in regular waves.

399. MCNATT, J.C., VENUGOPAL, V. & FOREHAND, D.: "The Cylindrical Wave Field of Wave Energy Converters", *10th EWTEC Conference, Aalborg, Denmark*, *vol. 03-Apr*, *issue. Special Issue*, pp. 26-39, DOI: 10.1016/j.ijome.2013.11.009, 2-5 Sep 2013

Knowledge of the wave field modification by a wave energy converter (WEC) is important to device and wave farm design. Cylindrical solutions to the linear wave field have long been used to analytically compute wave forces on circular-cylindrical geometries and have been the means of an important multi-body interaction theory. The cylindrical solutions are valid for an arbitrary geometry, but previous methods for computing the necessary coefficients were cumbersome. Herein, we present a new method for computing the cylindrical wave-field coefficients for an arbitrary geometry from a known circular-cylindrical section of the wave field. The method employs the Fourier transform and the orthogonality property of the depth dependence. The necessary circular-cylindrical section of the wave field is computed with the industry-standard boundary-element-method solver, WAMIT. Coefficients are computed for the radiated and scattered wave fields of four WECs, a heaving point absorber, a surging point absorber, a terminator, and an attenuator. The resulting cylindrical wave fields are compared over a large domain to wave fields computed completely by WAMIT and are found to be very accurate. The asymptotic representation of the cylindrical wave field is also considered and its range of accuracy is shown to depend the number of partial waves used to accurately represent the cylindrical wave field. Analytical solutions to the WEC wave field enable the use of interaction theories that accelerate WEC array computation and the integration with wave models that include additional physics.

400. MORETTI, G., FOREHAND, D., VERTECHY, R., FONTANA, M. & INGRAM, D.: "Modeling of an oscillating wave surge converter with dielectric elastomer power take-off", *33rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, California*, 8-13 June 2014
This paper introduces a novel concept of Oscillating Wave Surge Converter, named Poly-Surge, provided with a Dielectric Elastomer Generator (DEG) as Power Take-Off (PTO) system. DEGs are transducers that employ rubber-like polymers to conceive deformable membrane capacitors capable of directly converting mechanical energy into electricity. In particular, a Parallelogram Shaped DEG is considered. In the paper, a description of the Poly-Surge is outlined and engineering considerations about the operation and control of the device are presented. In addition, a mathematical model of the system is provided. Linear time-domain hydrodynamics is assumed for the primary interface, while a non linear electro-hyperelastic model is employed for the DEG PTO. A design approach for the Poly-Surge DEG PTO is introduced which aims at maximizing the energy produced in a year by the device in a reference wave climate, defined by a set of equivalent monochromatic wave conditions. A comparison is done with two other WEC models that employ the same primary interface but are equipped with mathematically linear PTO systems under optimal and suboptimal control. The results show promising performance of annual energy productivity, with slightly reduced values for the Poly-Surge, even if a very basic architecture and control strategy are assumed.

401. MURRAY, R.E., DOMAN, D.A., PEGG, M.J., GRACIE, K., & JOHNSTONE, C.M.: "Design of a Passively Adaptive Rotor Blade for Optimized Performance of a Horizontal-Axis Tidal Turbine", *10th EWTEC Conference, Aalborg, Denmark*, 2-5 Sep 2013
The rotor of an in-stream tidal turbine is the sole component which extracts power from the tidal flow, therefore optimization of turbine blade designs can result in more effective tidal extraction. Horizontal axis tidal turbines (HATT) typically have fixed pitch (FP) or variable pitch (VP) blades. Although FP blades require less maintenance and are typically less expensive than VP blades, they are limited to optimal performance at a specific tip speed ratio (TSR) and are exposed to high thrust loads at flow speeds above the design speed. Investigations have shown that active VP mechanisms improve the energy output of a device considerably and can decrease blade loads and power output at high flow speeds, however, they are complex and expensive. This paper sets out to report the outcomes of research being undertaken into rotor blades which self-adapt to varying flow conditions, called passively adaptive blades. Non-homogeneous tailored composite materials are being explored as a way to adapt the blade to operating conditions such that the angle of attack changes as a function of blade loading. This can potentially reduce the dynamic blade and structural loads and result in a predictable peak level of power above the design flow speed.

402. MURRAY, R.E., DOMAN, D.A., PEGG, M.J., NAVALAINEN, T.M., GRACIE, K. & JOHNSTONE, C.M.: "Design Tool for Passively Adaptive Turbine Blade.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
Tidal turbine blades made of composite materials can be tailored to couple flap-wise blade bending deformation with twisting, allowing the angle of attack to passively adapt as a function of hydrodynamic loading. Bend-twist (BT) coupling can decrease the loads on the blades and the support structure, resulting in a more cost effective device. This paper presents a finite element model (FEM)-blade element momentum theory (BEMT) based iterative design tool. This design tool was created to look at the interaction between the structural and hydrodynamic performance of passively adaptive tidal turbine blades. This tool decreases the computational time between design iterations at early stages of blade engineering compared to computational fluid dynamics based codes. Components of the BEMT and FEM codes have been verified independently, and BT blades designed using the coupled tool will be verified by prototype-scale testing in the next stages of this research.

403. NEVALAINEN, T.M., JOHNSTONE, C.M. & GRANT, A.D.: "An Unsteady Blade Element Momentum Theory for Tidal Stream Turbines with Morris Method Sensitivity Analysis.", *EWTEC conference, Nantes, France,*, 7-10 Sep 2015
In order to increase the reliability of Tidal Stream Turbines deployed in marine environments with instationary flow conditions, the impact of non-uniform loading on their components must be well understood. This paper explores the possibility of using an unsteady blade element momentum model to quantify the non-uniform loads a turbine would experience during operation and to ultimately show the consequent shaft load eccentricity. The model was verified against experimental data found in literature and was shown to be accurate when non-equilibrium wake effects caused by inflow velocity changes were considered. A Morris method sensitivity analysis was also performed on the model to investigate its sensitivity toward its input parameters and identify their importance in relation to the load output; the results showed that the model was most sensitive towards the turbine's rotational speed. Finally, the eccentricity of the loads on the shaft were shown to have a major upward directionality and also had a strong dependency on the turbine's rotational speed.

404. PASCAL, R., PAYNE, G., THEOBALD, C.M. & BRYDEN, I.: "Parametric models for the performance of wave energy converters", *Applied Ocean Research*, *vol. 38*, pp. 112-124, DOI: 10.1016/j.apor.2012.06.003, Oct-12
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 estimation has traditionally relied on only two sea state parameters, the significant wave height and the energy period, but these 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 the performance of WECs. Parametric models of the devices' performance were devised for numerous sea state parameters. These results suggest that the traditional estimation method should be extended in order to include at least a parameter related to the spectral bandwith.

405. PILLAI, A.C., CHICK, J., JOHANNING, L., KHORASANCHI, M. & DE LALEU, V.: "Offshore Wind Farm Electrical Cable Layout Optimization", *Engineering Optimization*, *vol. 47*, pp. 1689–1708, DOI: 10.1080/0305215X.2014.992892, 13/01/2015
This article explores an automated approach for the efficient placement of substations and the design of an inter-array electrical collection network for an offshore wind farm through the minimization of the cost. To accomplish this, the problem is represented as a number of sub-problems that are solved in series using a combination of heuristic algorithms. The overall problem is first solved by clustering the turbines to generate valid substation positions. From this, a navigational mesh pathfinding algorithm based on Delaunay triangulation is applied to identify valid cable paths, which are then used in a mixed-integer linear programming problem to solve for a constrained capacitated minimum spanning tree considering all realistic constraints. The final tree that is produced represents the solution to the inter-array cable problem. This method is applied to a planned wind farm to illustrate the suitability of the approach and the resulting layout that is generated.

406. RICHARDSON, D.S. & AGGIDIS, G.A.: "The economics of multi-axis point absorber wave energy converters", *32nd International Conference on Ocean, Offshore and Arctic Engineering, Nantes, France*, 9-14 June 2013
TRACT This paper examines the economic advantages and disadvantages of multi-axis point absorber wave energy converters in comparison to conventional heave-only point absorbers. A multi-axis point absorber wave energy converter (MA-PAWEC) is classified as a point absorber device that has a power take off (PTO) system extracting energy from more than one mode of motion (e.g. heave and surge). The majority of existing point absorber devices operate in heave mode alone. Therefore the forces exerted along other axes must be resisted by the mooring system, any reciprocal component of which constitutes a wasted opportunity to extract energy. The economics of PAWECs are governed by the available resource, energy generated by the device, capital cost and operational cost. These factors are examined for MA-PAWECs and compared to a generic heave-PAWEC. For a performance comparison, a simple generic body PAWEC is examined under heave mode operation and multi-axis operation in a representative spectrum. The modelling is based on linear potential theory. The potential advantages of MA-PAWECS are identified as greater energy absorption, fewer installed devices for a given capacity, and greater array control. Disadvantages include higher capex, higher maintenance costs and sensitivity to PTO costs. The performance and costs are assigned an estimated economic scaling factor and are applied to a generic heave-PAWEC for an economic comparison of the two devices. This indicates that a multi-axis approach to point absorbers could offer a 21% lower cost of electricity than the incumbent heave-response devices.

407. ROBINSON, A., INGRAM, D., BRYDEN, I. & BRUCE, T.: "The generation of 3D flows in a combined current and wave tank", *Ocean Engineering*, *vol. 93*, pp. 1-10, DOI: 10.1016/j.oceaneng.2014.10.008, Jan-15
One means of producing a 3D current in a circular tank is by using groups of conditioned axial flow impellers arranged around the perimeter to collectively create a sea representative bulk flow in a laboratory setting. Unfortunately to achieve the required bulk flow neighbouring impellers have to operate at different speeds resulting in steps in the plan view velocity profile. Therefore the underlying situation that governs tank behaviour is that of two fluid streams at different speeds combining, leading to a turbulent mixing layer which then dissipates and develops. Here a simulation of this flow is created using a 2D Reynolds Averaged Navier–Stokes method and then validated with physical experiments. The implications for accuracy and computational costs of various turbulence models, boundary conditions setups, and geometry representations are assessed. These findings are then used to produce a simplified 2D numerical model of the plan view flows in a 3D test tank which is then employed to demonstrate how a satisfactory device test zone might be generated from groups of stepped inputs. This finding helps prove that a combined current and wave tank can be created using the described configuration with the model providing a useful means of testing control scenarios.

408. ROBINSON, A., INGRAM, D., BRYDEN, I. & BRUCE, T.: "The effect of inlet design on the flow within a combined waves and current flumes, test tank and basins", *Coastal Engineering*, *vol. 95*, pp. 117-129, Jan-15
The motion of the sea, through waves and currents, represents a large source of clean and safe energy. However, any structure built to operate in the sea will experience large varying forces and a difficult environment. It is therefore crucial to develop realistic and repeatable sea-like conditions in a laboratory in order to lower the cost and risk of developing off-shore structures. Building on previous efforts, an experimentally validated numerical model is used to predict the current-only flow in flumes capable of combining waves and current. This model is then used to simulate the flows within common flume configurations and within a new concept known as the “isolating inlet flume”. The results of these simulations are then analysed to assess the performance of each flume type and to understand the fluid dynamics that govern each type. Flume performance is found to be largely determined by the creation and dissipation of shear layers. The tests proved that a flume using the isolating inlet requires significantly less downstream length to achieve a developed flow and acceptable turbulence levels than the previous flume configurations. The isolating inlet has the additional benefit of creating a still zone where a conventional wave-maker might be used. Further simulations are used to investigate the design of the isolating inlet flume and demonstrate how it works. This paper should be of use to scientists and engineers seeking to design flumes, test tanks and basins that create sea-like test conditions, thus improving the scope and range of laboratory testing.

409. SETHURAMAN, L. & VENUGOPAL, V.: "Hydrodynamic response of a stepped-spar floating wind turbine: Numerical modelling and tank testing", *Renewable Energy*, *vol. 52*, pp. 160-174, Apr-13
The hydrodynamic responses of a floating spar wind turbine under regular and irregular waves are measured by experimental techniques and the results are validated using the industry standard time-domain modelling tool, OrcaFlex. A 1:100 scale model is built with four mooring lines and tested in a wave tank for various wave conditions. The surge, heave and pitch motions of the spar model are measured using an optical tracking system both at its centre of mass and nacelle locations. The same motions are also simulated numerically using OrcaFlex under identical wave conditions. The measured hydrodynamic responses are evaluated as Response Amplitude Operator (RAO) and compared with numerical simulations. The results show a very good agreement in RAO between the experiments and numerical simulations. Comparison with existing literature for similar spar configuration indicates that the present study better captures the non-linearities from the mooring lines and the four-point mooring configuration is found to offer significant reduction in surge motions.

410. SPINNEKEN, J., CHRISTOU, M., & SWAN, C.: "Force-controlled absorption in a fully-nonlinear numerical wave tank", *Journal of Computational Physics*, *vol. 272*, pp. 127-148, *ISSN: 0021-9991*, Sep-14
An active control methodology for the absorption of water waves in a numerical wave tank is introduced. This methodology is based upon a force-feedback technique which has previously been shown to be very effective in physical wave tanks. Unlike other methods, an a-priori knowledge of the wave conditions in the tank is not required; the absorption controller being designed to automatically respond to a wide range of wave conditions. In comparison to numerical sponge layers, effective wave absorption is achieved on the boundary, thereby minimising the spatial extent of the numerical wave tank. In contrast to the imposition of radiation conditions, the scheme is inherently capable of absorbing irregular waves. Most importantly, simultaneous generation and absorption can be achieved. This is an important advance when considering inclusion of reflective bodies within the numerical wave tank. In designing the absorption controller, an infinite impulse response filter is adopted, thereby eliminating the problem of non-causality in the controller optimisation. Two alternative controllers are considered, both implemented in a fully-nonlinear wave tank based on a multiple-flux boundary element scheme. To simplify the problem under consideration, the present analysis is limited to water waves propagating in a two-

dimensional domain. The paper presents an extensive numerical validation which demonstrates the success of the method for a wide range of wave conditions including regular, focused and random waves. The numerical investigation also highlights some of the limitations of the method, particularly in simultaneously generating and absorbing large amplitude or highly-nonlinear waves. The findings of the present numerical study are directly applicable to related fields where optimum absorption is sought; these include physical wavemaking, wave power absorption and a wide range of numerical wave tank schemes.

411. STANSBY, P., CARPINTERO MORENO, E. & STALLARD, T.: "Capture width of the three-float multi-mode multiresonance broad-band wave energy line absorber M4 from laboratory studies with irregular waves of different spectral shape and directional spread.", *Journal of Ocean Engineering and Marine Energy*, *vol. 1*, *issue. 3*, pp. 287-298, DOI: 10.1007/s40722-015-0022-6, 2015
A moored multi-body line absorber is an attractive option for offshore wave energy conversion. Laboratory studies have been undertaken to determine capture width with multi-mode excitation and heave resonance for the three-float system M4 where the adjacent float spacing is about half a typical wavelength giving anti-phase forcing. The floats increase in diameter and draft from bow to stern and the bow and mid float are rigidly connected by a beam. A hinge with a damper above the mid float absorbs power from the relative rotation between the bow/mid float and the stern float. The resonant heave frequency for each float is different. Anti-phase surge forcing between mid and stern floats is substantial, while there is no hydrostatic stiffness producing resonance. This represents a hydrodynamically complex system and the laboratory experiments indicate high overall capture widths in irregular waves across a range of peak periods without damping optimisation. With different spectral peakedness and directional spread, the capture width is greater than 20 % of a wavelength (based on the energy period) across a range of peak periods typical of an offshore site for floats with a rounded base. The maximum capture width was about 37 % of a wavelength with rounded base floats; having rounded rather than flat bases increased energy capture by up to 60 % by reducing energy losses due to drag. For floats with flat bases comparisons with a geometrically scaled device five times larger and with similar magnitudes of equivalent damping showed similar capture widths as a proportion of wavelength.

412. STANSBY, P., CARPINTERO MORENO, E., STALLARD, T., MAGGI, A. & EATOCK TAYLOR, R.: "Wave energy conversion with high capture width by the three-float line absorber M4.", *Renewable Energies Offshore conference, Lisbon, Portugal*, Nov-14
A three-float line absorber with float spacing of about half a wavelength has been designed to capture energy due to forcing in heave, pitch and surge taking advantage of heave resonance. The floats increase in diameter and draft from bow to mid to stern float causing the device to head into waves. Heave resonance for the stern float is at a prominent wave period and for mid float at a somewhat lower wave period within the range for a wave climate. The bow and mid float are rigidly connected and power take off is from a hinge located above the mid float and connected by a beam to the stern float. Experiments at 1:8 and 1:40 scale show capture widths in irregular waves greater than 25% of a wavelength (based on energy period) for a broad range of frequencies typical of an offshore site.

413. STANSBY, P., GU, H., CARPINTERO MORENO, E. & STALLARD, T.: "Drag minimisation for high capture width with three float wave energy converter M4.", *EWTEC conference, Nantes, France*, 7-10 Sep 2015
The three float line absorber M4 has been tested experimentally for configurations with float bases which are flat and rounded. Rounded bases give capture width ratios (width of wave crest conveying extracted power divided by wavelength for the energy period) of up to 35% and greater than 20% across a broad frequency range. Near resonance values with rounded base are up to 60% greater than those for flat bases. Drag effects appear significant and here drag coefficients Cd for heave motion are investigated using VOF RANS CFD modelling. For forced oscillations CFD showed that Cd decreased as shapes changed from flat to rounded to hemispherical but were also dependent on kD (k is wavenumber and D is diameter). Results for a whole system model with flat bases using linear diffraction coefficients required a Cd of about 1.8 to agree with experimental average mechanical power output. This is different from CFD values for pure heave of about 0.3 but the system has more complex motion than simple heave with surge effects prominent. The Cd value for the system is a general coefficient. The need for experimental calibration of such highly efficient modelling is emphasised. For the rounded base float the radiation damping is greater than for the flat bases tested here and this will also be significant in increasing power output.

414. STANSBY,P.: "Surge based wave energy converter", *(Patent application PCT/GB2013/050787)*, 2013
A line absorber consisting of three cylindrical floats is shown to have high crest capture widths for wave energy conversion across a broad band of frequencies. The bow, mid and stern floats are small, medium and large respectively; the floats are spaced about half a wavelength apart so that forces and motion of adjacent floats are substantially in anti-phase. The bow and mid float are rigidly connected by a beam and a beam from the stern float is connected to a hinge above the mid float for power take off. The draft of the stern float enables heave

resonance at a prominent wave frequency and the smaller draft of the mid float provides resonance at a somewhat lower frequency.

415. STANSBY,P., CARPINTERO MORENO,E., STALLARD,T., & MAGGI,A.: "Three-float broad-band resonant line absorber with surge for wave energy conversion", *Renewable Energy*, *vol. 78*, pp. 132-140, Jun-15
A line absorber consisting of three cylindrical floats is shown to have high crest capture widths for wave energy conversion across a broad band of frequencies. The bow, mid and stern floats are small, medium and large respectively; the floats are spaced about half a wavelength apart so that forces and motion of adjacent floats are substantially in anti-phase. The bow and mid float are rigidly connected by a beam and a beam from the stern float is connected to a hinge above the mid float for power take off. The draft of the stern float enables heave resonance at a prominent wave frequency and the smaller draft of the mid float provides resonance at a somewhat lower frequency. Experimental results at about 1:8 scale show capture widths greater than 25% of a wavelength in regular waves and greater than 20% of a wavelength in irregular waves across a broad range of wave periods. A time-stepping model for regular waves with coefficients from linear diffraction theory showed similar power prediction with a generic drag coefficient of 1.8. The model shows the importance of surge forcing and heave resonance. The model also shows that reducing drag coefficient will increase capture width.

416. STRATIGAKI, V., TROCH, P., STALLARD, T., FOREHAND, D., FOLLEY, M., VANTORRE, M., KOFOED, J.P., BABARIT, A. & BENOIT, M.: "Development Of A Point Absorber Wave Energy Converter For Investigation Of Array Wake Effects In Large Scale Experiments", *4th International Conference on the Application of Physical Modelling of Port and Coastal Protection (Coastlab12), Ghent, Belgium*, 17-20 Sep 2012
Wave energy from ocean waves is absorbed by using Wave Energy Converters (WECs). In order to extract a considerable amount of wave power at a location, in a cost-effective way, large numbers of WEC's have to be arranged in array using a particular geometric configuration. Interactions between the individual WEC's ("near field effects") affect the overall power production of the array. In addition, the wave height reduction behind an entire WEC array ("far field effects") may affect other users in the sea, the environment or even the coastline. Several numerical studies on large WEC arrays have already been performed, but large scale experimental studies, focussing on "near-field" and "far-field" wake effects of large WEC arrays are not available in literature. Within the HYDRALAB IV FP7 European programme, the WECwakes research project has been introduced, in order to perform experiments on large arrays of point absorber WEC's, using different geometric configurations and inter-WEC spacings. The selected facility is the Shallow Water Wave Basin of the Danish Hydraulic Institute (DHI), in Denmark. The results from the WECwakes experimental tests will be useful in the validation and extension of the recently developed numerical models, as well as in providing insight to optimising the geometric configurations of WEC arrays for power production, and at quantifying the related environmental impact. The present paper focuses on the preparation of the WECwakes project and the development of the used WEC models.

417. THIES, P.R., JOHANNING, L. & MCEVOY, P.: "A novel mooring tether for peak load mitigation: Initial performance and service simulation testing.", *International Journal of Marine Energy*, DOI: 10.1016/j.ijome.2014.06.001, 2014
One of the main engineering challenges for floating marine renewable energy devices is the design of reliable, yet cost-effective mooring solutions for the harsh and dynamic marine environment. The mooring system must be able to withstand the ultimate limit state during storm conditions as well as the fatigue limit state due to the highly cyclic wave induced motions. This paper presents the performance and service simulation testing of a novel mooring tether that combines the material properties of elastomeric and thermoplastic elements. This allows to 'tailor' the load-extension curve to exhibit a low stiffness response for the expected normal, operating, load conditions and a high stiffness response for the envisaged extreme, storm, conditions. The experimental results demonstrate the working principle of the mooring element and show good agreement between the theoretical load extension curve and the conducted performance tests with a distinct hysteresis effect caused by the thermoplastic element. The hysteresis is dependant on the applied pre-tension and load cycle amplitude of the element and to a lesser extent on the cycle frequency. The relaxation of the elastomeric element is quantified, giving insight into the expected long-term performance of the tether. The demonstrated working principle and the possibility to tailor the mooring response allows engineers to load- and cost-optimise the mooring system of floating marine energy converters.

418. WATERS, S., & AGGIDIS, G.: "A World First: Swansea Bay Tidal lagoon in review.", *Renewable and Sustainable Energy Reviews*, *vol. 56*, pp. 916-921, DOI: 10.1016/j.rser.2015.12.011, Apr-16
Global energy focus is turning more and more towards renewable energy. With legally binding agreements requiring a drastic increase in the percentage of national energy demand created with renewable sources, tidal energy holds an important advantage – predictability. The UK is fortunate, having the greatest potential for this energy in the world, which if exploited, would be able to provide approximately 20% of the national energy demand. The most discussed tidal energy site has been the Severn estuary barrage, with repeated proposals

outlined and rejected throughout the last 100 years. The reasons for this refusal were due to both high costs and environmental concerns. However, a new proposal for a tidal lagoon in Swansea Bay has been able to circumnavigate both of these downfalls by reducing both the investment needed and effects to the surrounding environment. Subject to a tidal range of 10.5 m and situated next to a largely populated city with excellent grid connections, Swansea bay is a perfect location. If the lagoon project goes ahead, it would be able to produce a rated output of 320 MW using bulb turbines, powering 155,000 homes. Being the first tidal lagoon project, what is certain is: the UK and Wales in particular are sending out a strong message regarding renewable energy and it has the whole worlds attention. This paper sets out to bring together current literature regarding the planned Swansea Bay tidal lagoon into one concise document.

419. WATERS, S., & AGGIDIS, G.: "Tidal range technologies and state of the art in review", *Renewable and Sustainable Energy Reviews*, *vol. 59*, pp. 514-529, DOI: 10.1016/j.rser.2015.12.347, Jun-16
Tidal range technology has seen much development and interest in recent years. The times when a barrage scheme would be rejected due to environmental and cost concerns is coming to an end. A large variety of new lower cost and less invasive methods have since emerged in the forms of tidal lagoons, reefs and fences. Since the construction of La Rance in 1967, advancements in turbine technologies and design has since resulted in a plethora of new, exciting turbine designs for tidal energy. A selection of new turbines with possible tidal range applications includes the modified bulb turbine with two sets of guide vanes, a counter-rotating turbine, Archimedes screw and a gyro device. However, the same design is continuously being chosen – the Kaplan bulb turbine. Through the use of a marking criterion covering key aspects that should be considered when choosing a turbine a variety of the new designs available are investigated. The key aspects researched include, environmental effects, the two-way efficiency, initial costs and maintenance costs/difficulty.

420. WEISS, G., LI, G., MUELLER, M., TOWNLEY, S., & BELMONT, M.R.: "Optimal control of wave energy converters using deterministic sea wave prediction", *Fuelling the Future: Advances in Science and Technologies for Energy Generation, Transmission and Storage*, pp. 396-400
We demonstrate that deterministic sea wave prediction (DSWP) combined with constrained optimal control can dramatically improve the efficiency of sea wave energy converters (WECs), while maintaining their safe operation. Our analysis concerns a WEC consisting of a float moving vertically against a heave plate and employing a hydraulic/electric power take-off system. Maximising energy take-off while minimising the risk of damage is formulated as an optimal control problem with a disturbance input (the sea elevation) and with both state and input constraints. We demonstrate that a nearly optimal control is of bang-bang type. This paves the way to adopt a dynamic programming (DP) algorithm to resolve the on-line optimization problem efficiently. Simulation results show that this approach is very effective, yielding at least a two-fold increase in energy output as compared to control schemes which do not exploit DSWP.

421. YAVUZ, H., MISTIKOGLU, S., THORPE, T., AGGIDIS, G. & STALLARD, T.: "Wave Energy: Available Technologies and R&D Status", *Energy Science and Technology, Volume 9, Geothermal and Ocean Energy*, pp. 460-501, *ISBN: 1-62699-070-0*, 2015
The increasing awareness of environmental issues attracts more attention on environment-friendly energy sources. This leads to increasing research on effective use of renewable energy sources. Amongst these sources, wave energy offers a high potential. The wave energy converter systems used for transforming the wave energy into electrical energy have been a research topic for decades. Although hundreds of different types of wave energy systems are reported in the literature, only a few of these systems have been successfully implemented. This chapter first looks at the potential of wave energy and discusses the challenges facing this technology. Then, it reviews some of the selected wave energy devices proposed. It also discusses the achievements made by the Wave Energy Research Groups around the world.

422. ZVE, E.S. & SPINNEKEN, J.: "Towards long random sea simulations in numerical wave tanks", *The Twenty-sixth (2016) International Ocean and Polar Engineering Conference*, *ISSN: 1098-6189*, 26-Jun-16
The present investigation concerns optimum wave absorption in numerical wave tanks. Recent developments have now established that (i) absorption controllers based on Infinite Impulse Response (IIR) filters are highly effective and (ii) cosh shaped wave board geometries offer significant potential in terms of active wave absorption due to their favourable added mass behaviour. While (i) and (ii) have been shown individually, their combination has never been demonstrated. To address this, a cosh shaped wave-maker is implemented in a time-domain numerical wave tank. Comparisons are presented between simple proportional controllers and the IIR approach, where the latter is demonstrated to offer excellent absorption performance over a very broad range of incident wave conditions. In excess of 90% amplitude (or equivalently 99% energy) absorption is demonstrated for the range $1 \leq kh \leq 8$, where k is the wave number and h is the water depth. A broad-banded absorption performance of this type covers the vast majority of wave components present in practical offshore wave spectra. Test cases are presented for both regular and irregular seas, paving the way towards numerical simulations of long random sea states. This

paper focuses on a two-dimensional description of the problem. The approach adopted can also be extended to three dimensions, where reduced domain sizes (no sponge layer requirements) offer orders of magnitude improvement in terms of computational cost.

Appendix 3 Alphabetical listing of publications

ABANADES, J., GREAVES, D. & IGLESIAS, G.: "Wave farm impact on the modal state of a beach", Marine Geology, vol. 361, pp. 126–135, 01-Mar-15 (Arrays and farms)

ABANADES, J., GREAVES, D. & IGLESIAS, G.: "Coastal defence using wave farms: The role of farm-to-coast distance", Renewable Energy, pp. 572-582, 2015 (Environmental Interaction)

AFGAN, I., MCNAUGHTON, J., ROLFO, S., APSLEY, D.D., STALLARD, T. & STANSBY, P.K.: "Turbulent flow and loading on a tidal stream turbine by LES and RANS", International Journal of Heat and Fluid Flow, vol. 43, pp. 96-108, DOI: 10.1016/j.ijheatfluidflow.2013.03.010, 17-Jun-13 (Extreme loadings and durability)

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AGGIDIS, G.A.: "Ocean Energy Research and State of the Art.", International THRUST 2015, Thessaloniki, Greece, May-15 (Arrays and farms)

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